Introduction to Space Resource Mining

International Space University
Space Studies Program - SSP13

STRASBOURG, FRANCE

JULY 15, 2013

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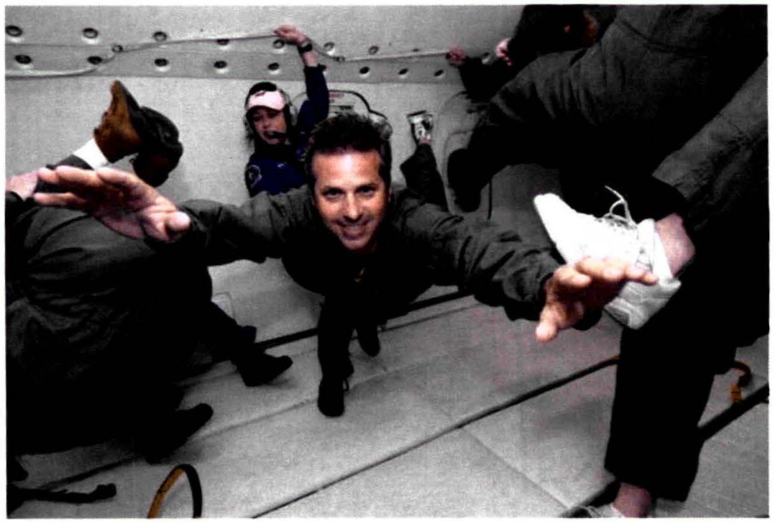
SURFACE SYSTEMS OFFICE - NASA

KENNEDY SPACE CENTER, FLORIDA, USA

Introduction



- NASA Senior Technologist specializing in Space Mining, Robotics, Regolith, In-Situ Resource Utilization and Space Systems Engineering
- B.Sc. Mechanical Engineering – University of Miami, Florida, USA
- M.S. Space Systems Engineering – TU Delft, Netherlands, EU
- M.B.A. Business Administration - Florida Institute of Technology, USA
- Worked at Kennedy Space Center (KSC), Johnson Space Center (JSC) & Jet Propulsion Lab (JPL) since 1989

Introduction

- The Swamp Works is a new KSC facility designed for Innovation and Lean Development of New Space Technologies
- KSC Swamp Works establishes rapid, innovative and cost effective exploration mission solutions through leveraging of partnerships across NASA, industry and academia
- New way of doing business – back to the future:

Wernher Von Braun and Kelly Johnson both used these methods

Mission

The NASA Mission

Drive advances in science, technology, and exploration to enhance knowledge, education, innovation, economic vitality, and stewardship of Earth.

Overarching Strategies

- **Investing in next-generation technologies** and approaches to spur innovation
- **Inspiring students** to be our future scientists, engineers, explorers, and educators
- **Expanding partnerships** with international, intergovernmental, academic, industrial, and entrepreneurial communities
- **Committing to environmental stewardship**
- **Securing the public trust** through transparency and accountability

Why Resources ?

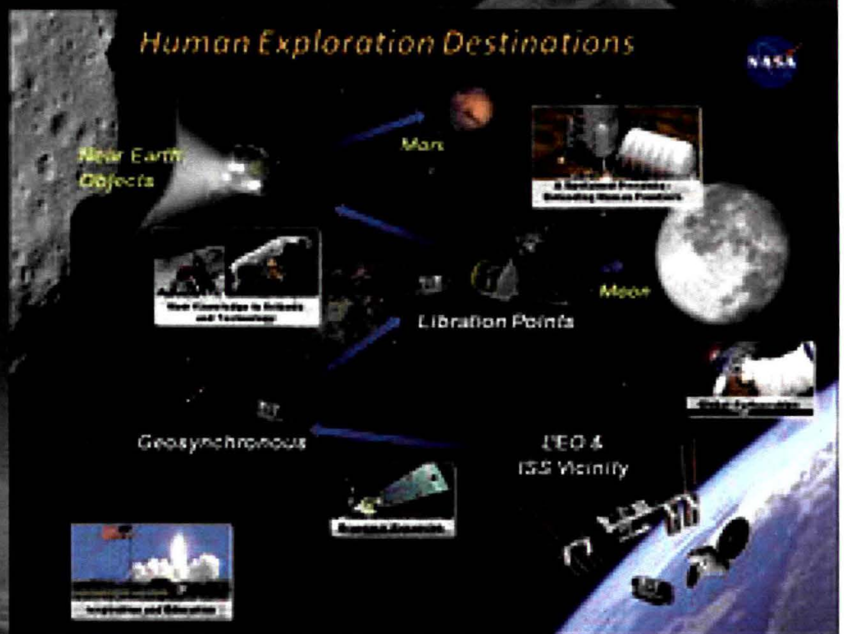
NASA Strategic Goals:

- Extend and sustain human activities across the solar system
- Create the innovative new space technologies for our exploration, science, and economic future

Affordable and Sustainable

Critical for exploration beyond low Earth orbit

- **Robotics & Automation**
- **Power Systems**
- Propulsion
- Habitation & Life Support
- **Space Resource Utilization**



A New Level of Civilization

Where are the Resources?

Resources

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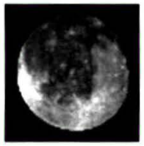
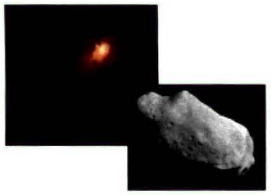
Possible Destinations

Moon



Mars & Phobos

Near Earth Asteroids & Extinct Comets



Europa

Titan

Common Resources

Water
- Moon
- Mars
- Comets
- Asteroids
- Europa
- Titan
- Triton
- Human Habitats

Carbon
- Mars (atm)
- Asteroids
- Comets
- Titan
- Human Habitats

Metals & Oxides
- Moon
- Mars
- Asteroids

Helium-3
- Moon
- Jupiter
- Saturn
- Uranus
- Neptune

Core Building Blocks

- Atmosphere & Volatile Collection & Separation
- Regolith Processing to Extract O_2, Si, Metals
- Water & Carbon Dioxide Processing
- Fine-grained Regolith Excavation & Refining
- Drilling
- Volatile Furnaces & Fluidized Beds
- 0-g & Surface Cryogenic Liquefaction, Storage, & Transfer
- In-Situ Manufacture of Parts & Solar Cells

Core Technologies

- Microchannel Adsorption
- Constituent Freezing
- Molecular Sieves

- Hydrogen Reduction
- Carbothermal Reduction
- Molten Oxide Electrolysis

- Water Electrolysis
- CO_2 Electrolysis
- Sabatier Reactor
- RWGS Reactor
- Methane Reformer
- Microchannel Chem/thermal units

- Scoopers/buckets
- Conveyors/augers
- No fluid drilling

- Thermal/Microwave Heaters
- Heat Exchangers
- Liquid Vaporizers

- O_2 & Fuel Low Heatleak Tanks (0-g & reduced-g)
- O_2 Feed & Transfer Lines
- O_2/Fuel Couplings

Water on Earth

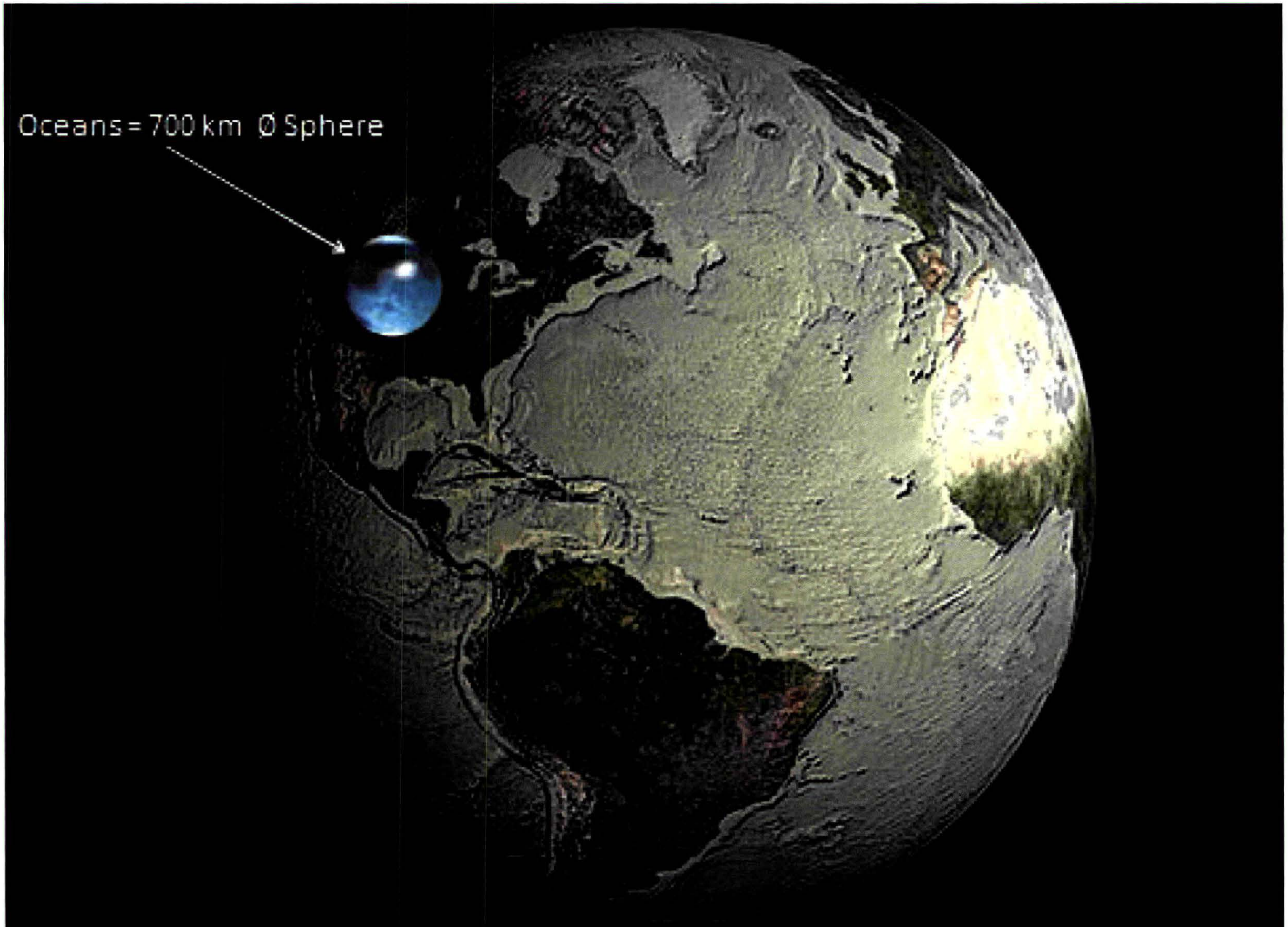
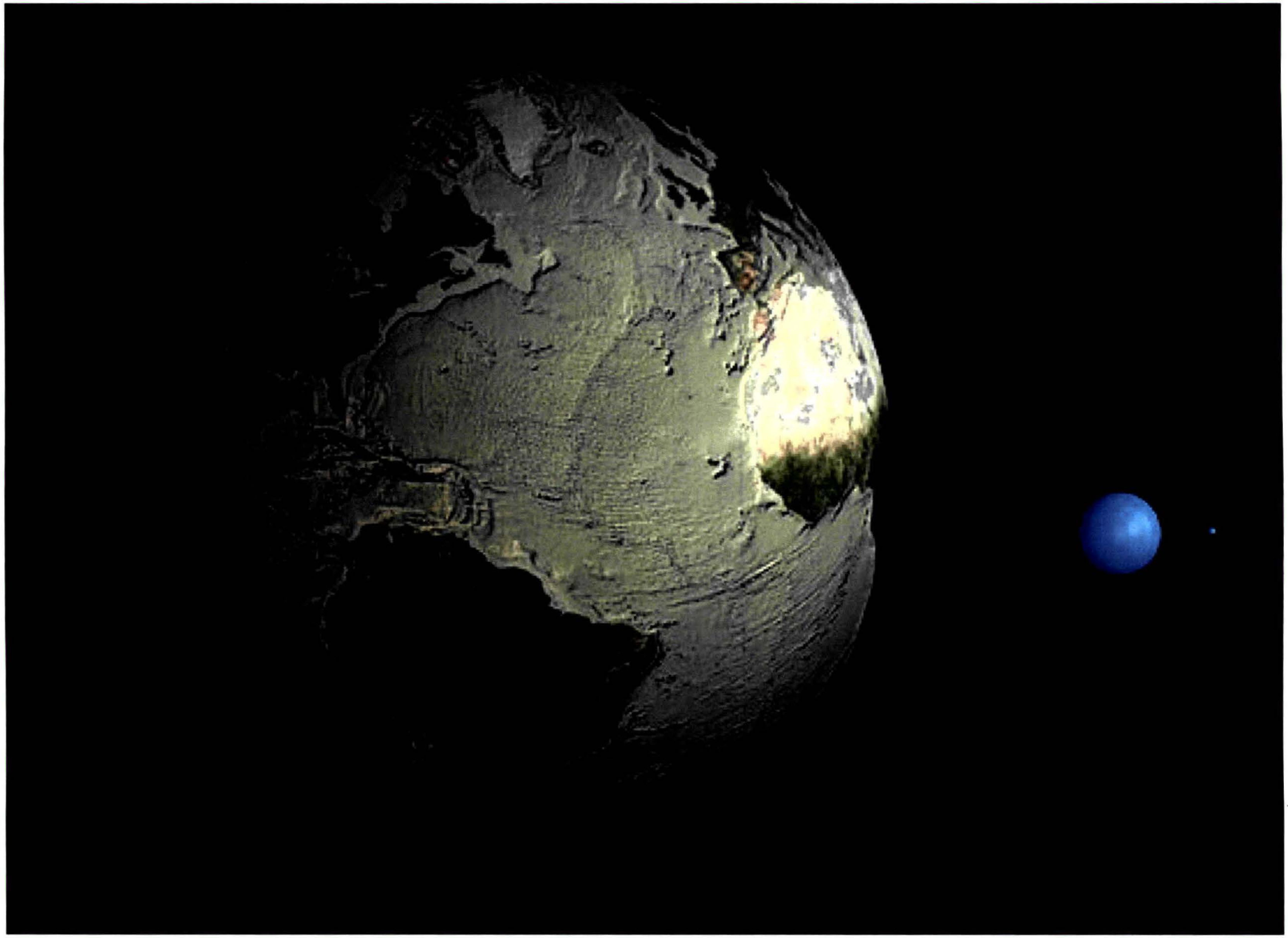
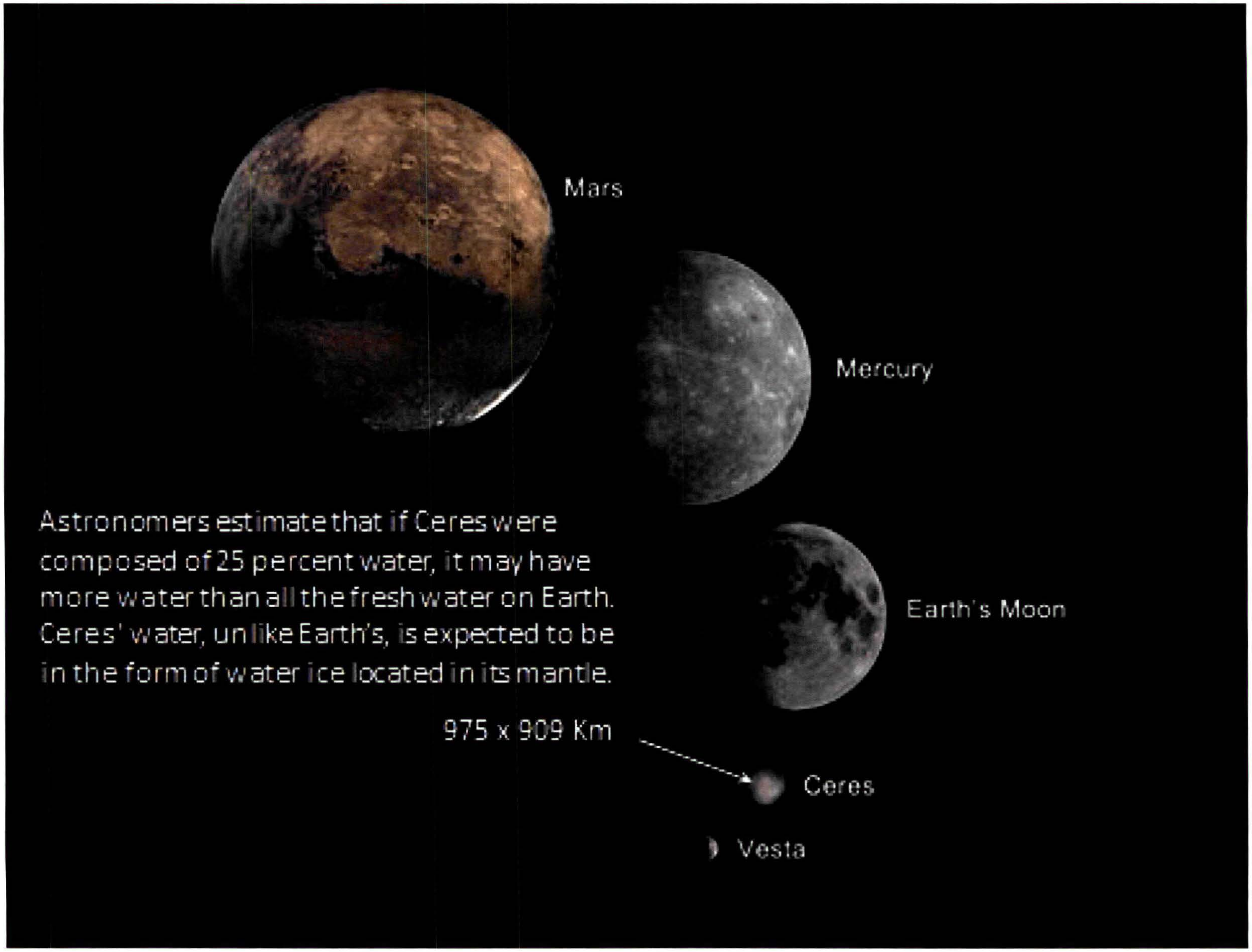


Illustration by Jack Cook, Woods Hole Oceanographic Institution

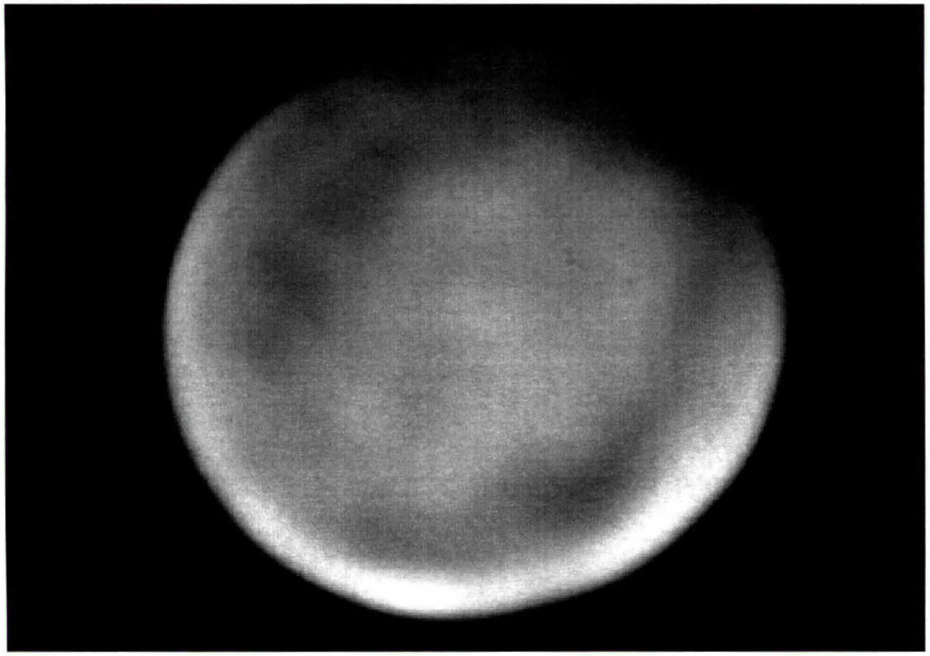
Water on Earth



Water on Ceres?



Comets & Asteroid H_2O Resources

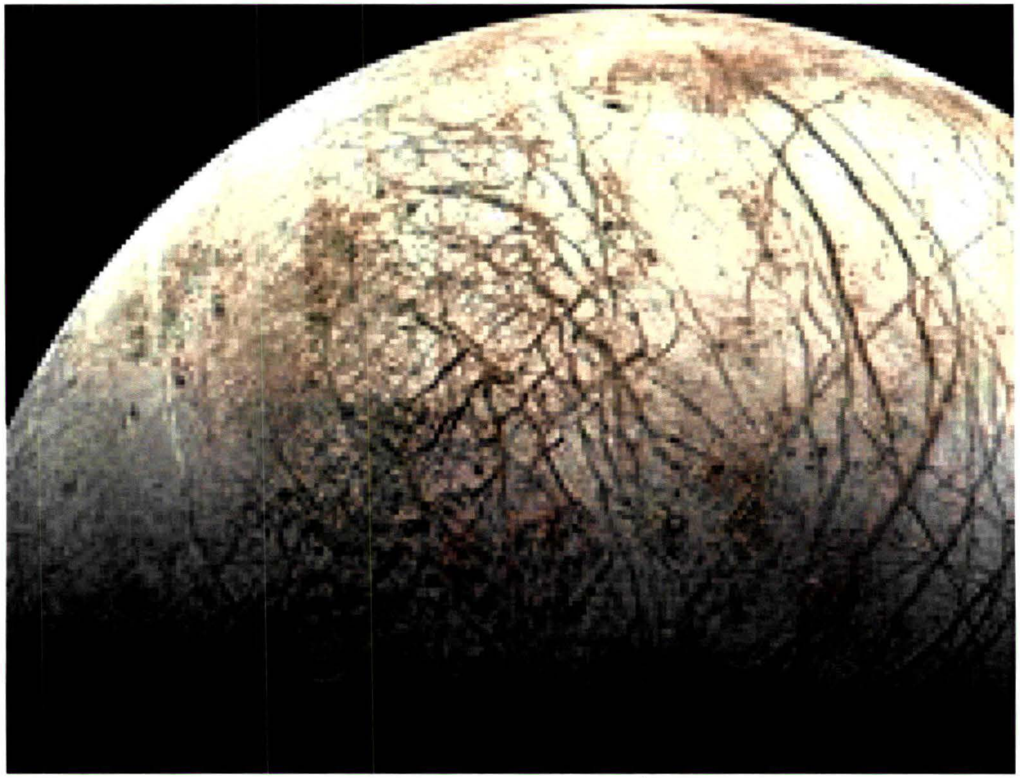


Ceres Telescope Image: Dawn Mission to investigate in 2015!

NASA Deep Impact & Stardust (Wild 2)

JAXA Hayabusa
25143 Itokawa

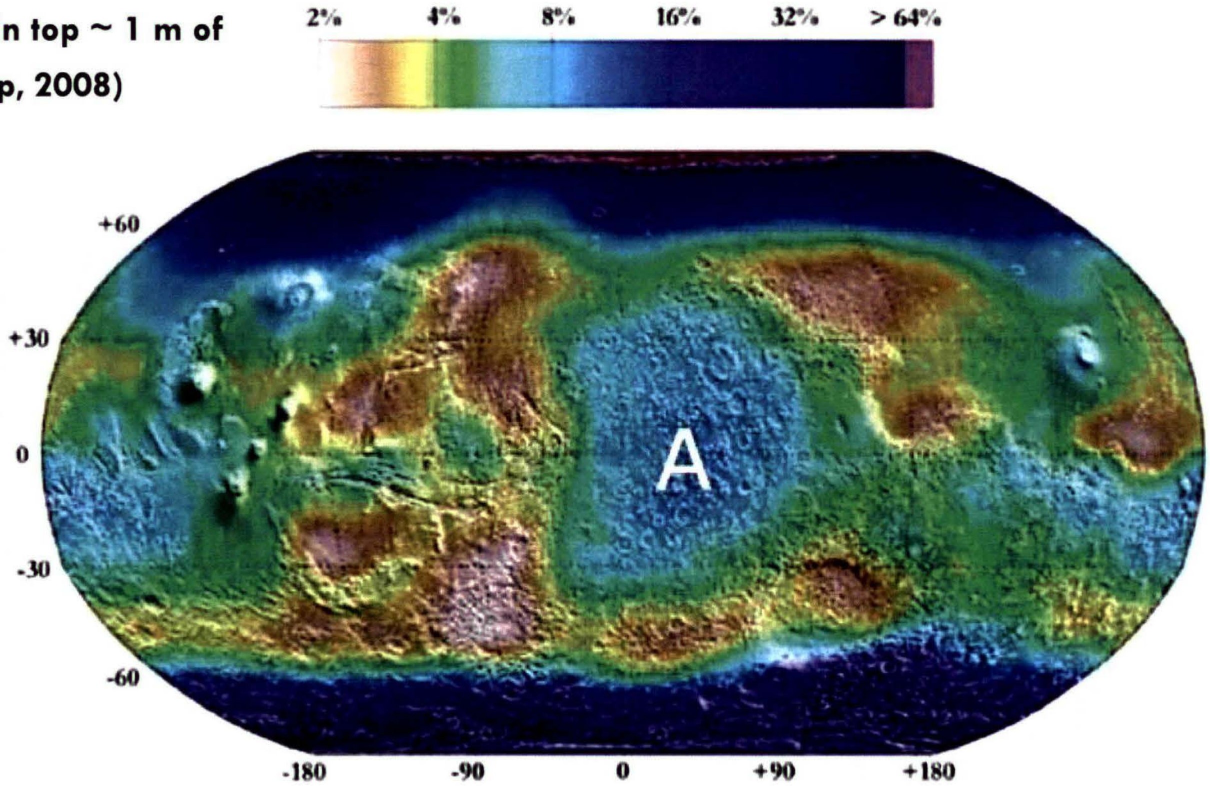
Europa H_2O Resources

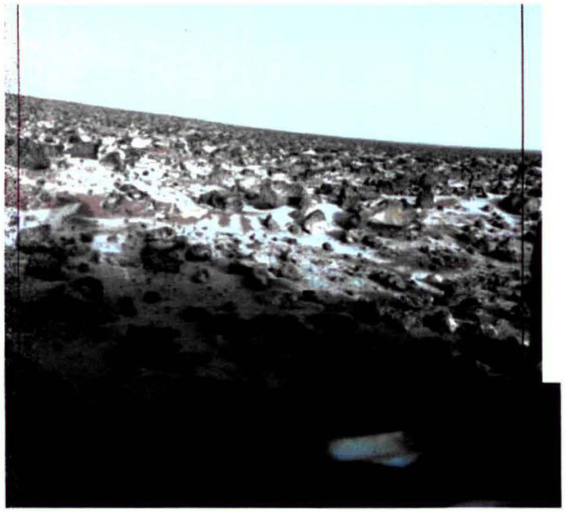


Europa, as viewed from NASA's Galileo spacecraft. Visible are plains of bright ice, cracks that run to the horizon, and dark patches that likely contain both ice and dirt. Image Credit: NASA

Mars H_2O Resources

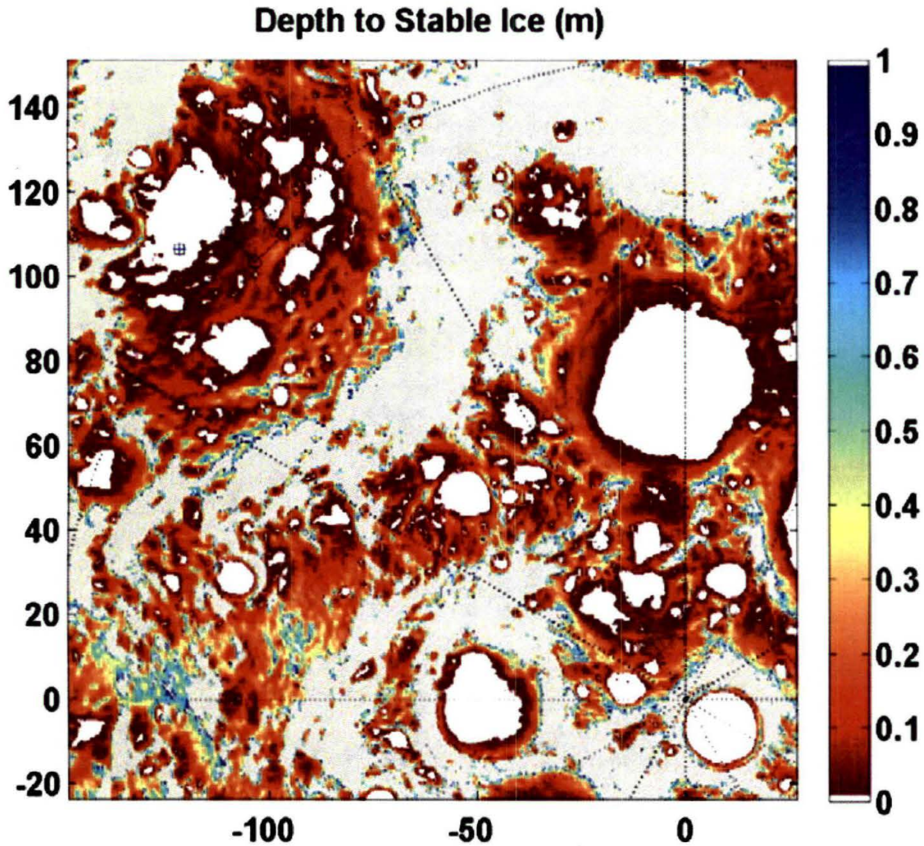
Measured H2O content in top ~ 1 m of Mars in 5x5 pixels (Rapp, 2008)



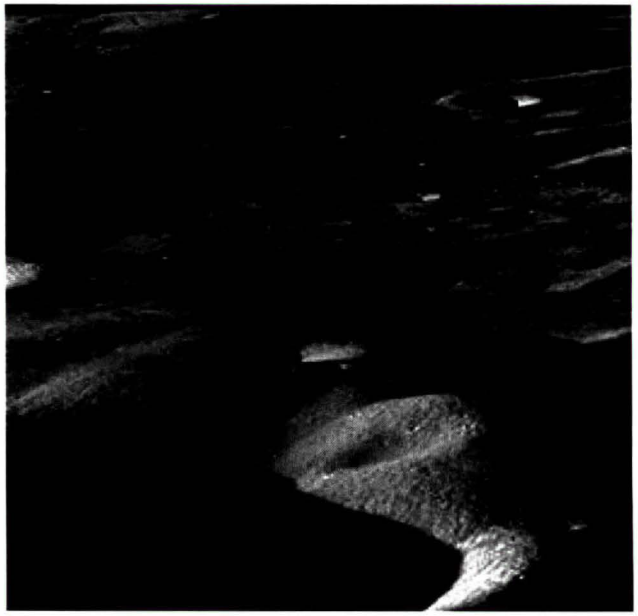


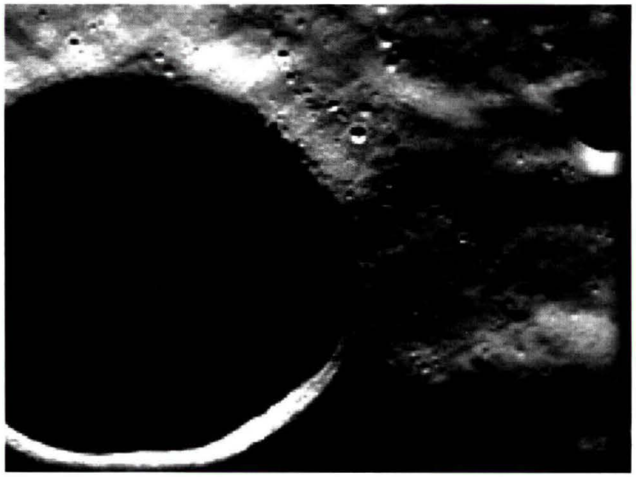
Water Snow on *Viking* 2 landing site in May, 1979 (NASA Photo ID 211093)11. *Viking* scoop dug 15 cm while it is expected the ice-cemented ground is at 24 cm depth. (Zacny, 2012)

Moon H_2O Resources



Depth (m) to the 1 kg/m2 per billion year ice loss isotherm, from [2]. White denotes stability within 1 cm of the surface, beige indicates stability below 1m [3].





Our Evolving Understanding of the Moon and it's Resources

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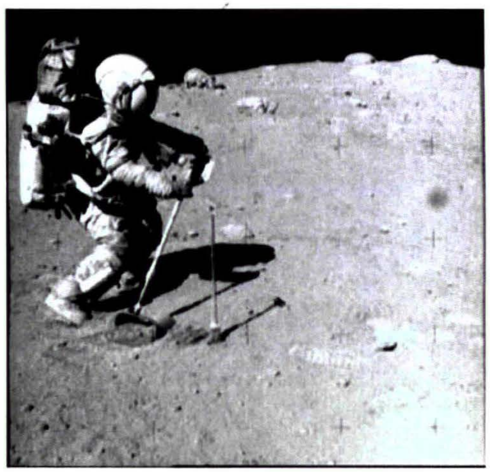
1961: 1970 1994 1998 2008 2009 2010

In a 1961 paper, Watson, Murray and Brown theorize that cold traps at the moon's poles may contain water ice

Apollo samples, 1969-1972 point to a bone dry Moon



Our Evolving Understanding of the Moon and it's Resources

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Missions to the Moon in the 1990's provided intriguing data that suggested the permanently shadowed regions of the Moon may harbor water ice and other volatiles

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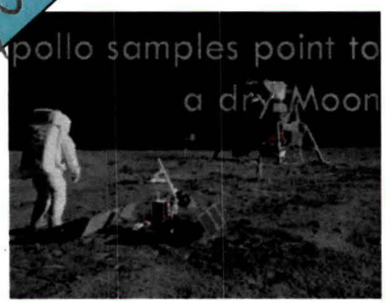
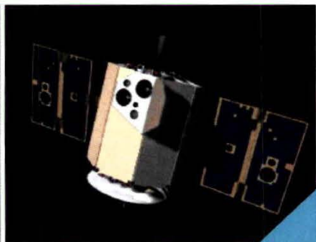
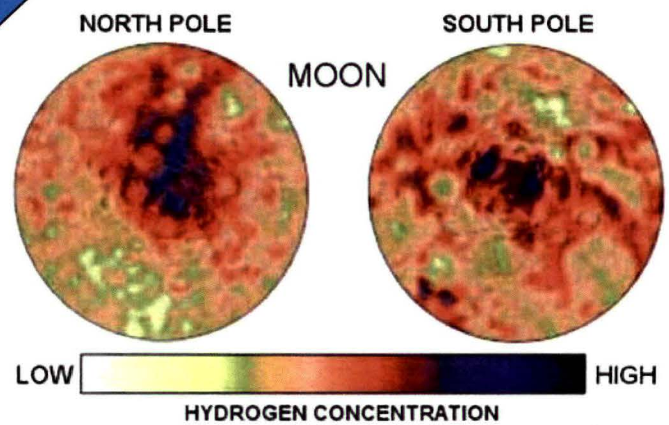


Clementine Bi-Static Radar suggest Water Ice in permanently shadowed regions near the poles





Neutron Spectrometer aboard Lunar Prospector detects elevated levels of hydrogen that correlates with permanent shadow

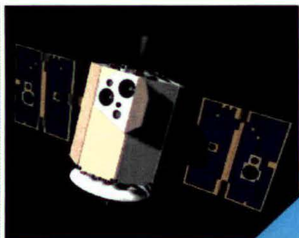
Our Evolving Understanding of the Moon and it's Resources

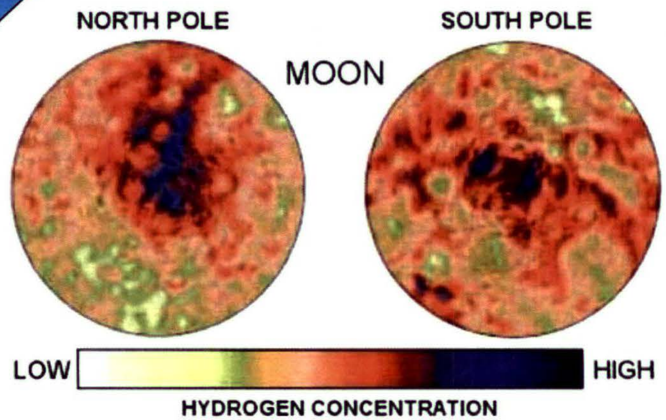
Conclusions drawn from Clementine and Lunar Prospector regarding lunar water ice was vigorously debated.

Planetary Scientist, Larry Taylor, says he will "eat his shorts if there is water on the moon."

1961: 1970 1994 1998 2008 2009 2010

Clementine Bi-Static Radar suggest Water Ice in permanently shadowed regions near the poles





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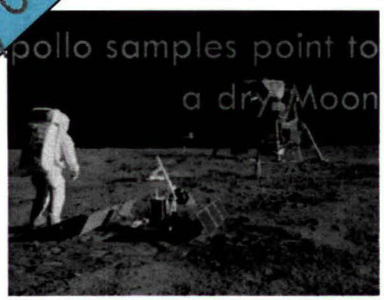

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Our Evolving Understanding of the Moon and its Resources

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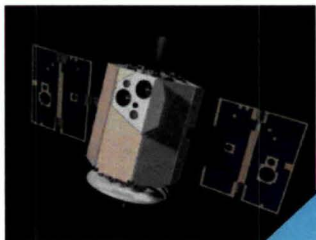
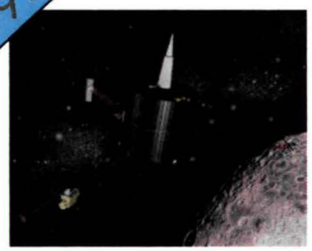


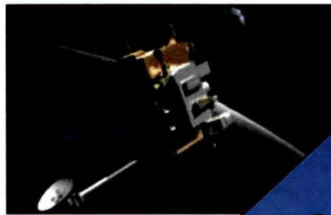
Clementine's Bi-Static Radar suggest Water Ice in permanently shadowed regions near the poles



Neutron Spectrometer aboard Lunar Prospector detects elevated levels of hydrogen that correlates with permanent shadow

Synthetic Aperture Radar on Chandrayaan 1 returns data that is consistent with water ice in the PSR's

LCROSS impacts Cabeus A and clearly detects significant quantities of water in the ejecta



Integrated data sets from instruments on LRO support the existence of large quantities of water ice in the PSRs and in partially sunlit regions

LCROSS & LRO Definitively Prove Existence of Volatiles at the Lunar Poles

					Instrument			
	Column Density (# m^{-2})	Relative to H2O(g) (NIR spec only)	Concentration (%)	Long-term Vacuum Stability Temp (K)	UV/Vis	NIR	LAMP	M3
CO	1.7e13±1.5e11		5.7	15			x	
H_2O(g)	5.1(1.4)E19	1	5.50	106		x		
H_2	5.8e13±1.0e11		1.39	10			x	
H_2S	8.5(0.9)E18	0.1675	0.92	47	x	x		
Ca	3.3e12±1.3e10		0.79				x	
Hg	5.0e11±2.9e8		0.48	135			x	
NH_3	3.1(1.5)E18	0.0603	0.33	63		x		
Mg	1.3e12±5.3e9		0.19				x	
SO_2	1.6(0.4)E18	0.0319	0.18	58		x		
C_2H_4	1.6(1.7)E18	0.0312	0.17	~50		x		
CO_2	1.1(1.0)E18	0.0217	0.12	50	x	x		
CH_3OH	7.8(42)E17	0.0155	0.09	86		x		
CH_4	3.3(3.0)E17	0.0065	0.04	19		x		
OH	1.7(0.4)E16	0.0003	0.002	>300 K if adsorbed	x	x		x
H_2O (adsorb)			0.001-0.002					x
Na		1-2 kg		197	x			
CS					x			
CN					x			
NHCN					x			
NH					x			
NH_2					x			

Volatiles comprise possibly 15% (or more) of LCROSS impact site regolith

Our Evolving Understanding of the Moon and its Resources

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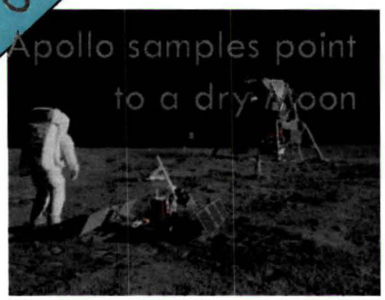
1961:

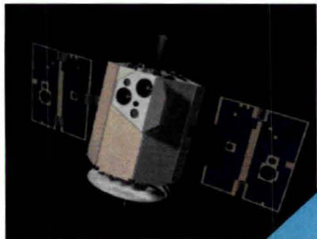
Watson, Murray and Brown theorize that cold traps at the moon's poles may contain water ice

1970



1994

Clementine's Bi-Static Radar suggest Water Ice in permanently shadowed regions near the poles



1998

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2009

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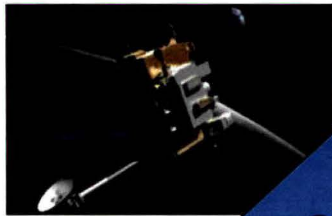
2010

Integrated data sets from instruments on LRO support the existence of large quantities of water ice in the PSRs and in partially sunlit regions

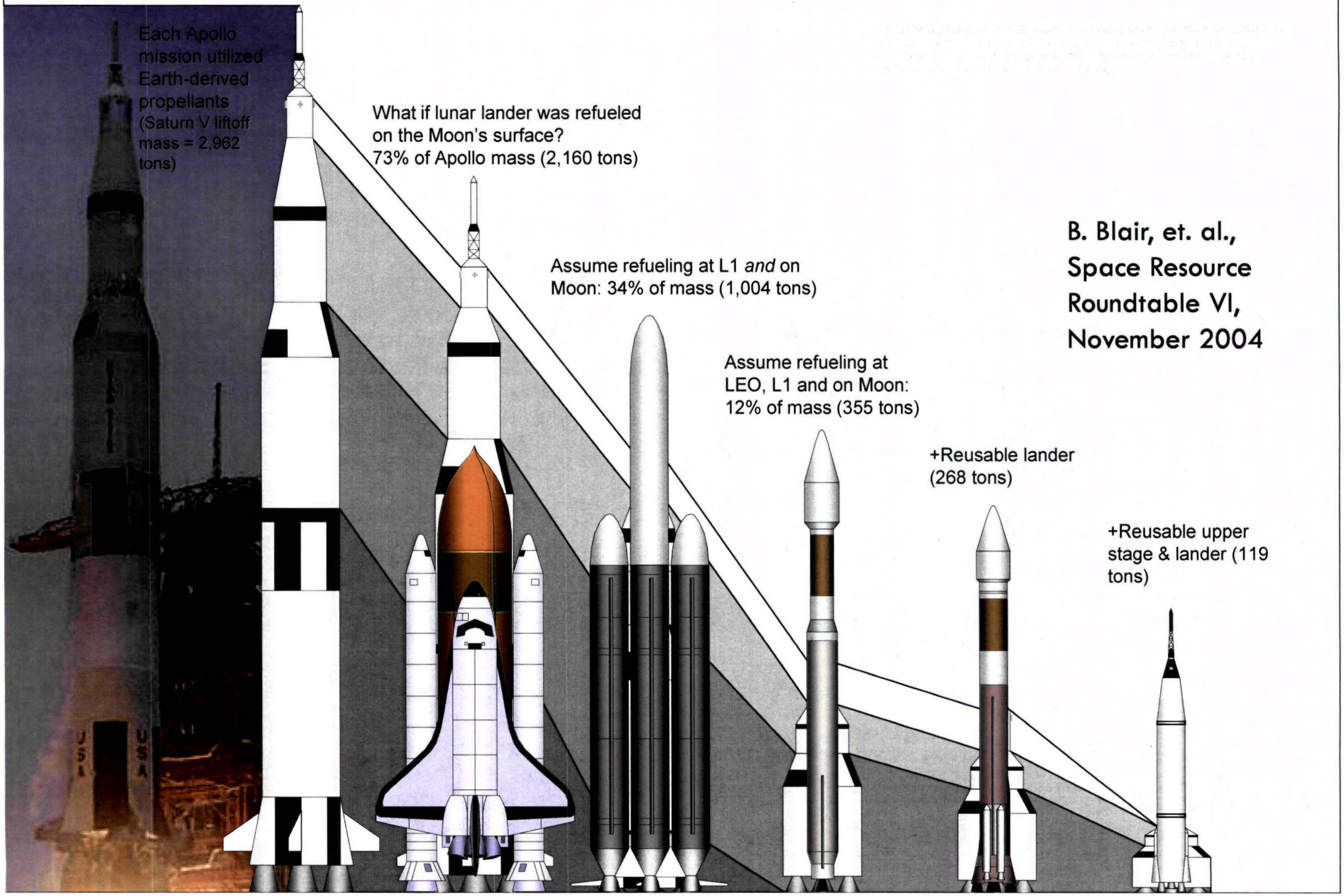


Larry Taylor is served a cake decorated as a pair of shorts at a Lunar Planetary Institute meeting

Importance of Lunar Volatiles as a Resource

- Water is Life
  - Oxygen to breath
  - Water to drink
  - Water for cooling systems
  - Water for radiation shielding
  - Water for plants
- Volatiles can be used to manufacture propellant
  - Water is an easy form for the transportation of hydrogen & oxygen
  - Water can be converted into hydrogen and oxygen using abundant solar power in orbit
  - Hydrogen & Oxygen can be liquefied in space and stored in propellant depot
  - Orbital depots open up a commercial market for propellants
  - Alternatively, the hydrogen from the water can be combined with plentiful carbon monoxide to make methane, another useful propellant.
- Harvesting resources at our destinations can dramatically change the our mission architectures.

Propellant from the Moon will revolutionize our current space transportation approach

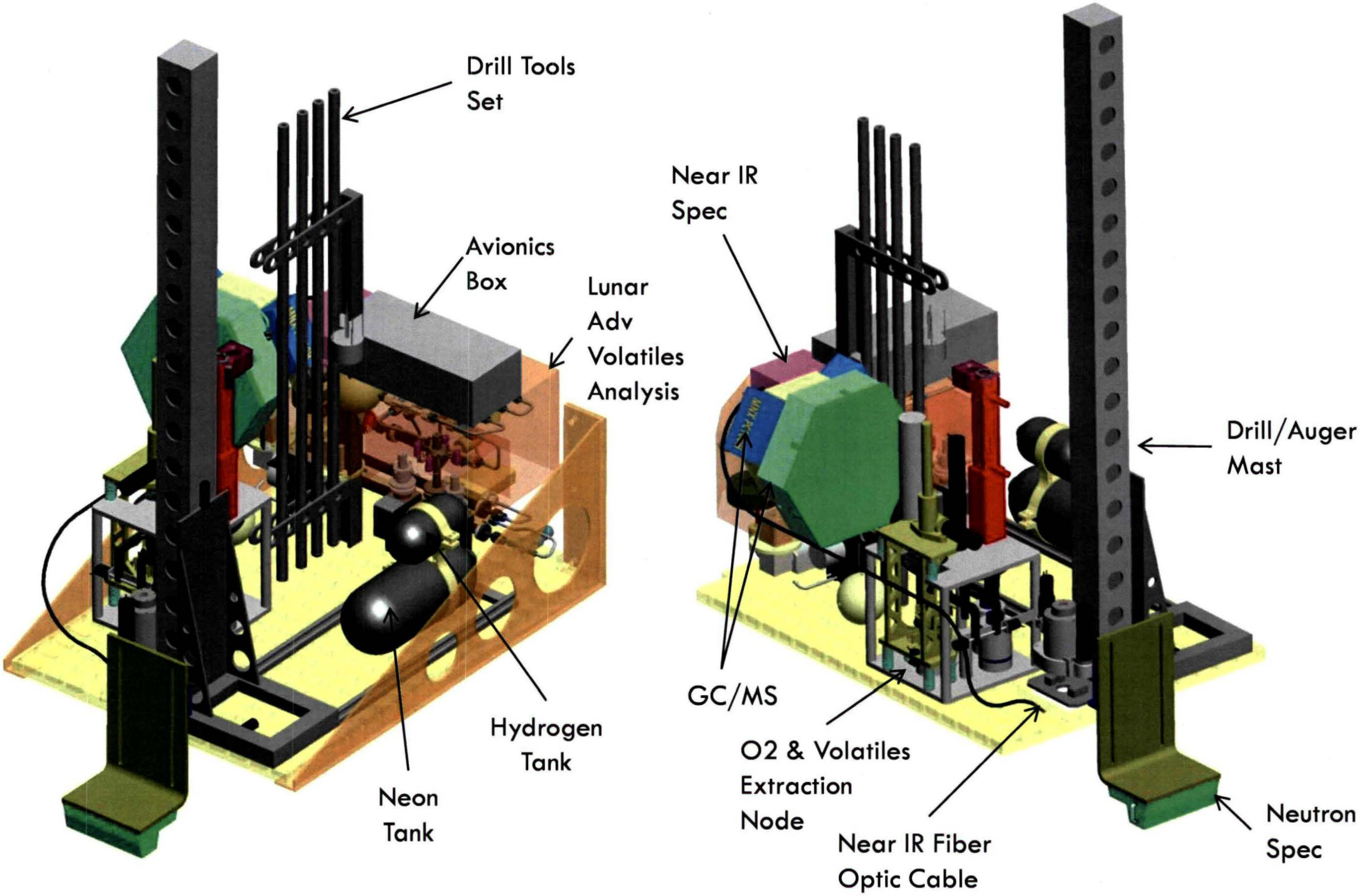


B. Blair, et. al., Space Resource Roundtable VI, November 2004

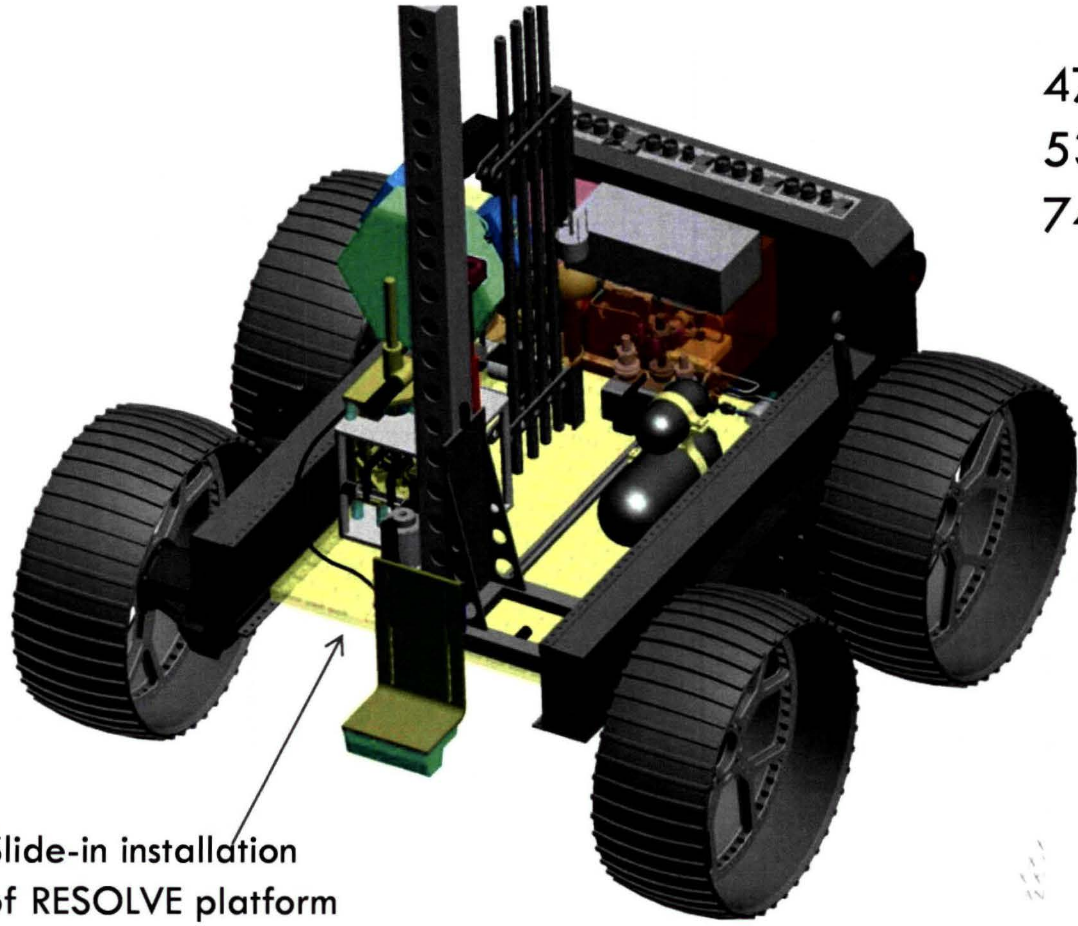
What's the Next Step?

- We now know with certainty that there are volatiles at one spot on the moon.
- Comparison's of orbital instrument data with the LCROSS plume seem to suggest that the water is not evenly distributed.
- Until we know the distribution and accessibility of the volatiles don't really know if we have a usable resource.
- A "Ground Truth" surface mission is the next logical step.
- RESOLVE is the payload that NASA and the CSA are designing to answer these questions

RESOLVE Payload Layout



RESOLVE Integrated with CSA Rover



470mm Length
533mm Width
746mm Height

Slide-in installation
of RESOLVE platform
To CSA Rover

RESOLVE Integrated with CSA Rover

Actual Photo on Mauna Kea

RESOLVE Mission Options – Potential South Pole Landing Sites

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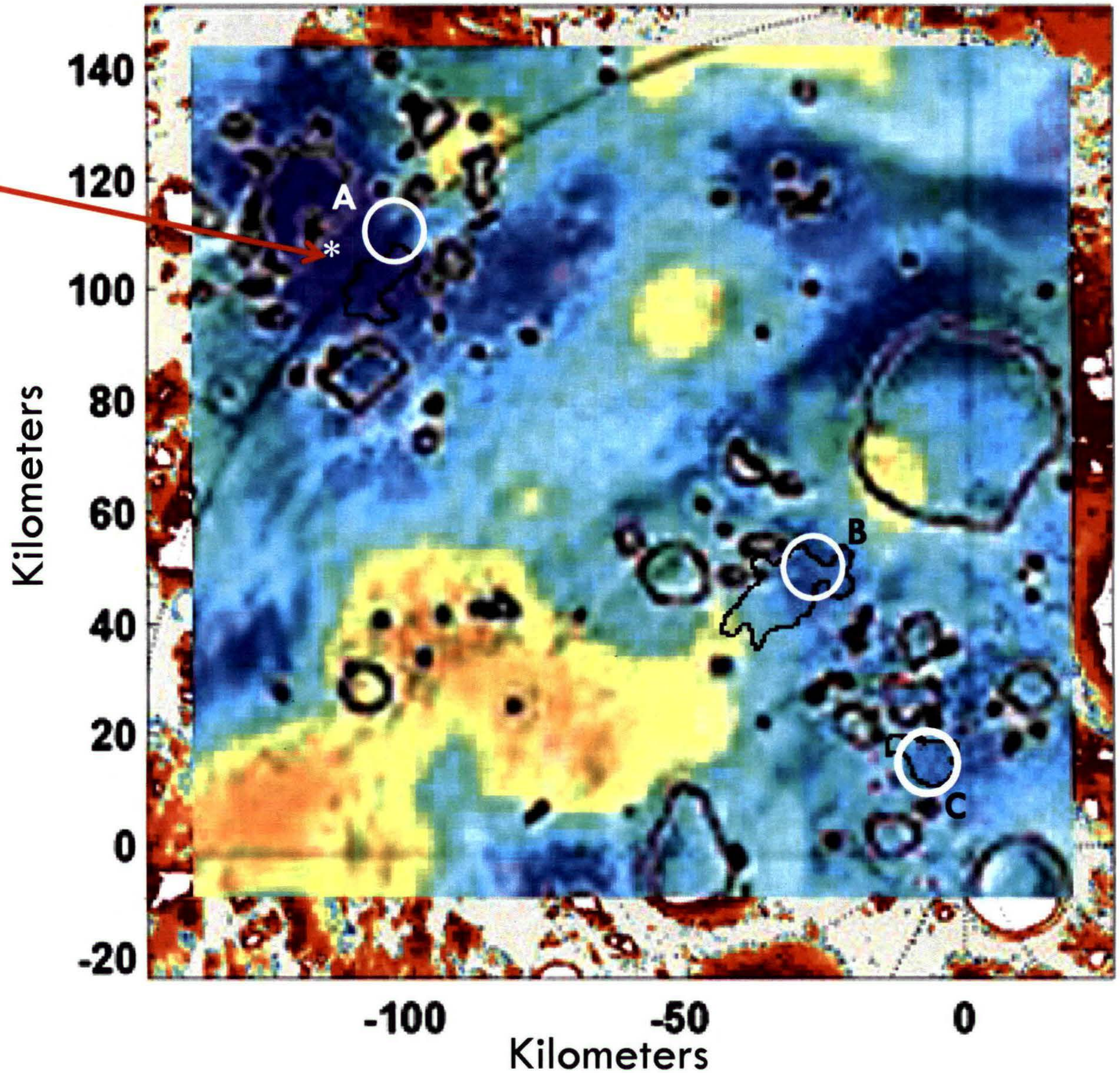
Neutron Depletion

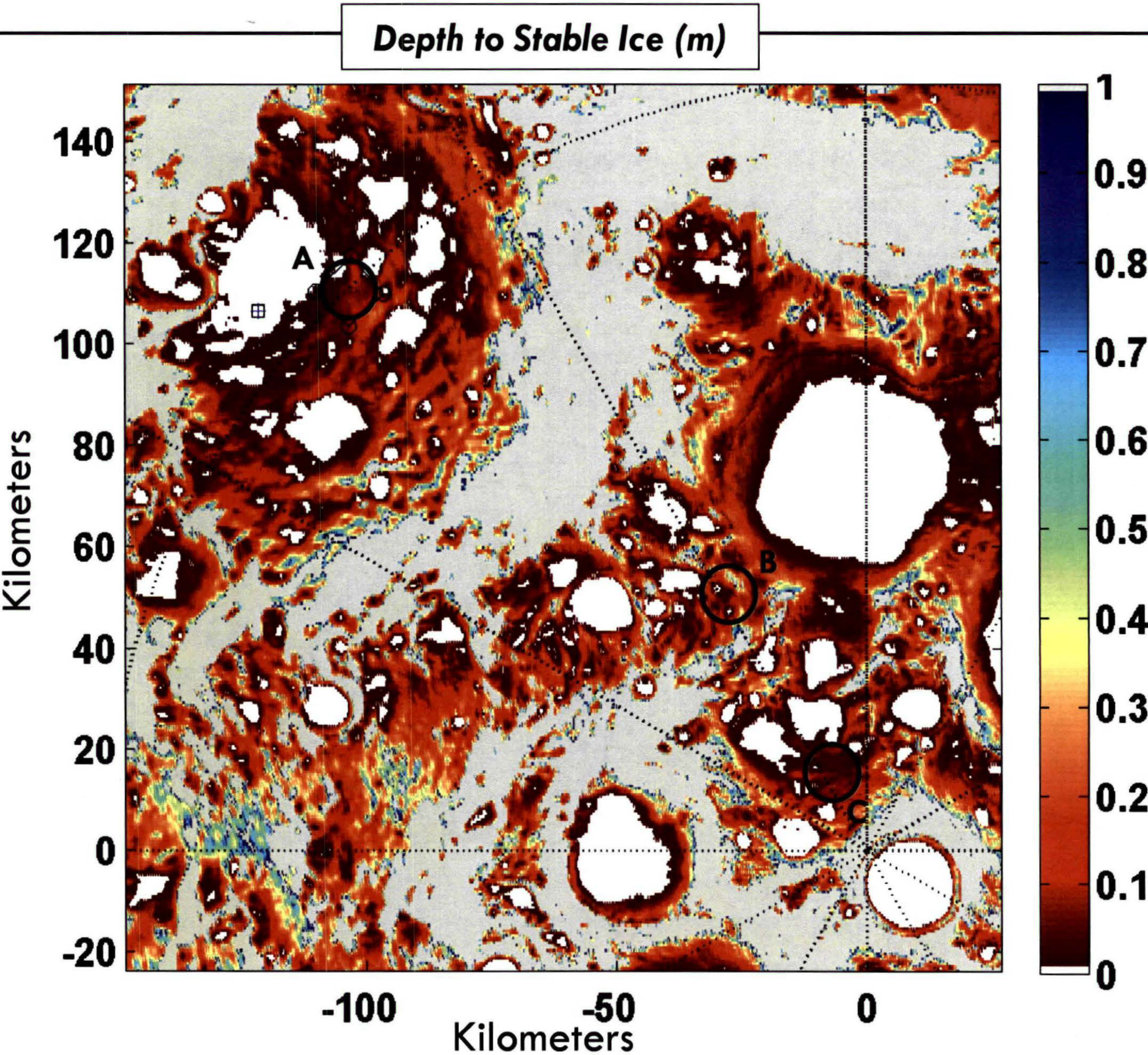
LCROSS impact site



Dark blue represent the areas of highest neutron suppression

Circles A, B & C selected for closer examination

RESOLVE Mission Options – Potential South Pole Landing Sites



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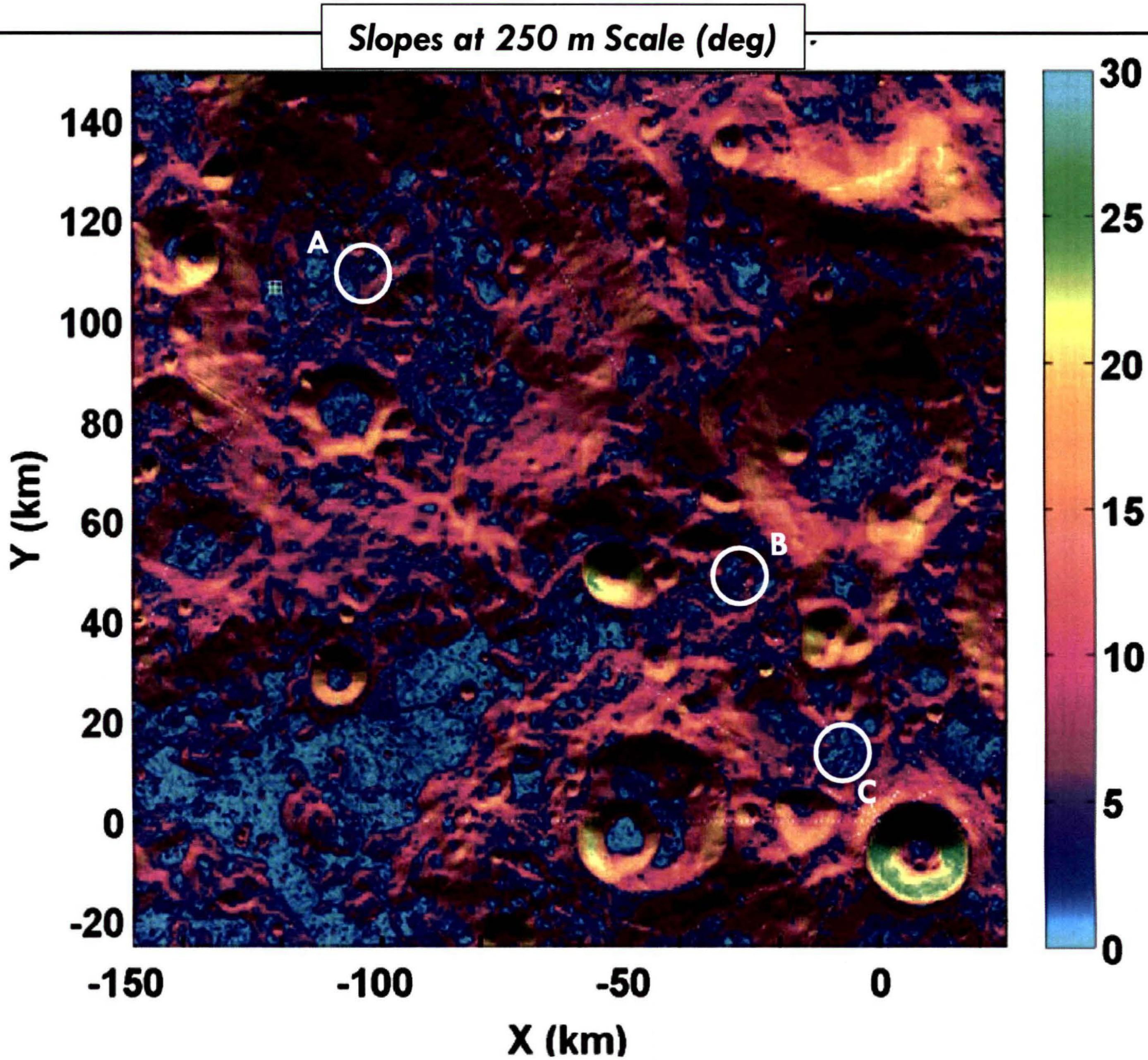

RESOLVE Mission Options – Potential South Pole Landing Sites

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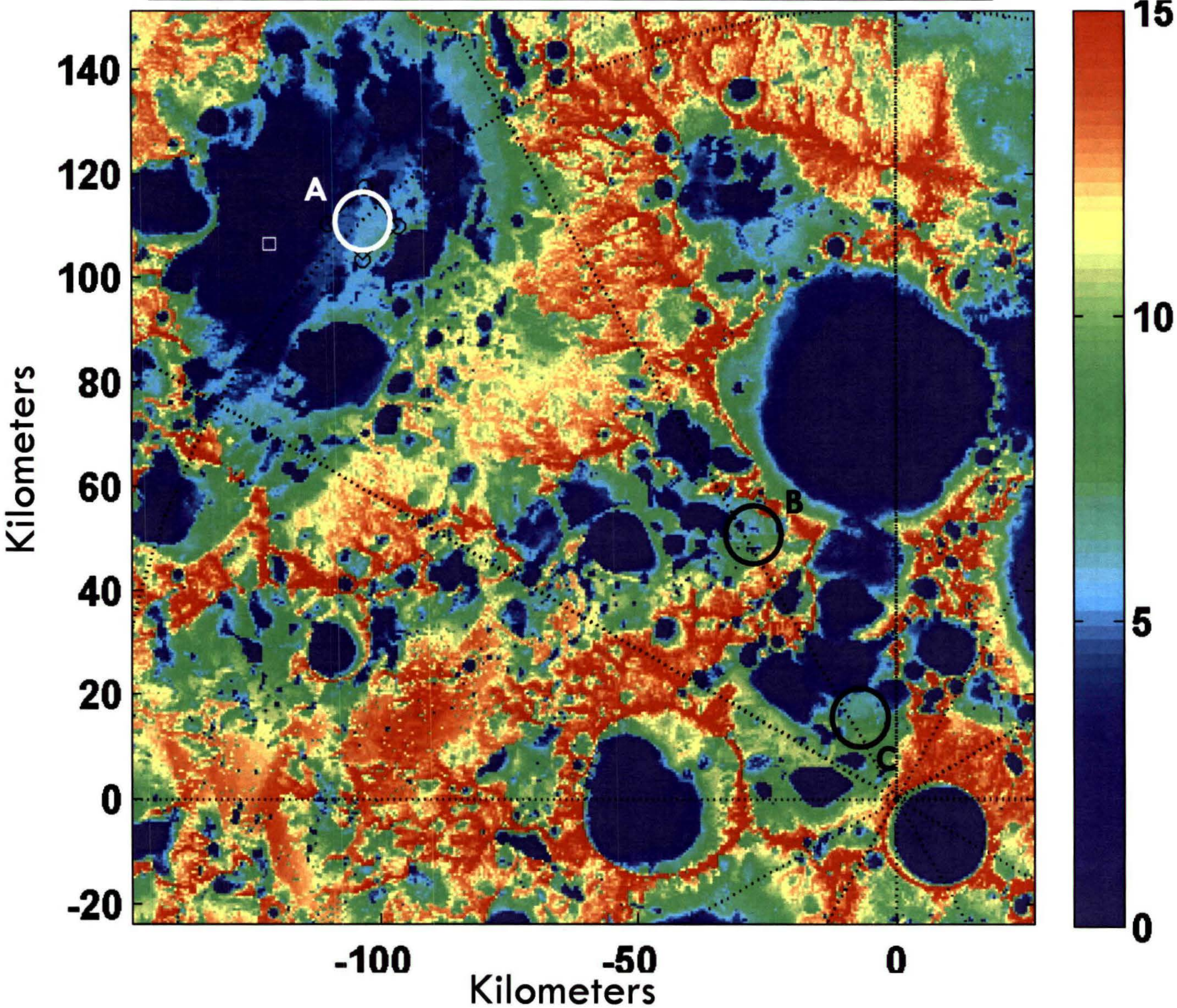
Maximum Days of Sunlight Using LOLA DEM



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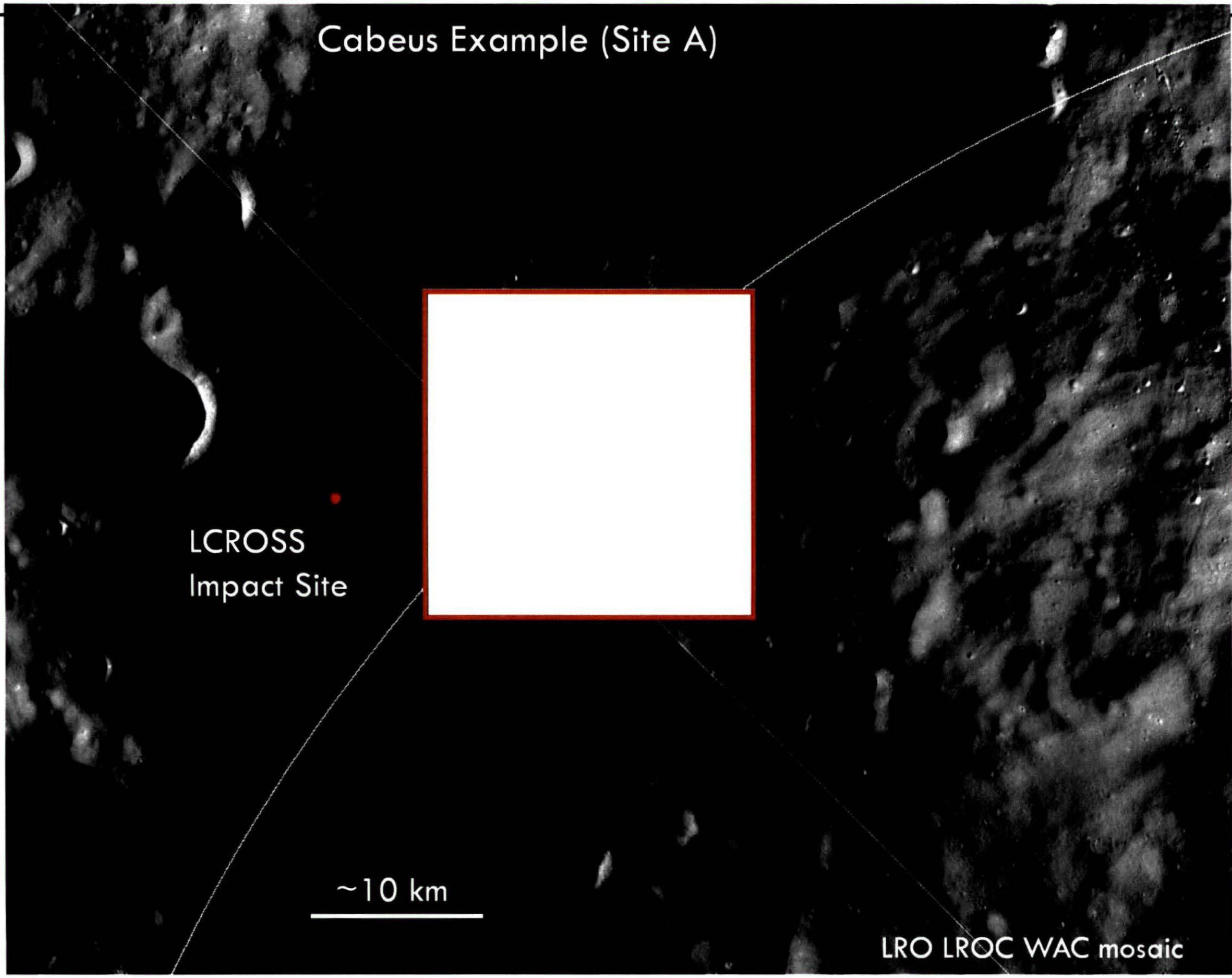

Sun and Shadow Ops

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SUN (2.5 days)

- **Checkout**
  - *6.17 hrs*

- **1st Navigation 0.6 km**
  - *3.88 hrs, 0.6 km total*
- **Drill 1st Hole 4.33 hrs**
  - *Two 0.5m Augers (1-2)*
  - One 1.0m Core (1)
- **Process Segments (1-8)**
  - *8 segments, 26.84 hrs*

- **2nd Navigation 0.6 km**
  - *3.88 hrs, 1.2 km total*
- **Drill 2nd Hole 4.33 hours**
  - *Two 0.5m Augers (3-4)*
  - One 1.0m Core (2)
- **Process Segments (9-10)**
  - *2 segments, 9.59 hrs*

SHADOW (2 days)

- **Hibernate**
  - *48 hrs*

- *Consider using this "down time" to downlink detailed RESOLVE data (pics, detailed plant data, etc.)*

SUN (5 days)

- **Battery Recharge**
  - *6.8 hrs*

- **3rd Navigate 0.6 km**
  - *3.88 hrs, 1.8 km total*
- **Drill 3rd Hole 4.33 hrs**
  - *Two 0.5m Augers (5-6)*
  - One 1.0m Core (3)
- **Process Segments (11-15)**
  - *5 segments, 19.85 hrs*
  - *1st H2 Reduction*

- **4th Navigate 0.2 km**
  - *2.29 hrs, 2.0 km total*
- **Drill 4th Hole 4.33 hrs**
  - *Two 0.5 m Augers (7-8)*
  - One 1.0m Core (4)
- **Process Segments (16-20)**
  - *5 segments, 19.85 hrs*
  - *2nd H2 Reduction*

- **5th Navigate 1.0 km**
  - *5.47 hrs, 3.0 km total*
- **Drill 5th Hole 4.33 hrs**
  - *Two 0.5m Augers (9-10)*
  - One 1.0m Core (5)
- **Process Segments (21-25)**
  - *5 segments, 18.41 hrs*
  - *3rd H2 Reduction*

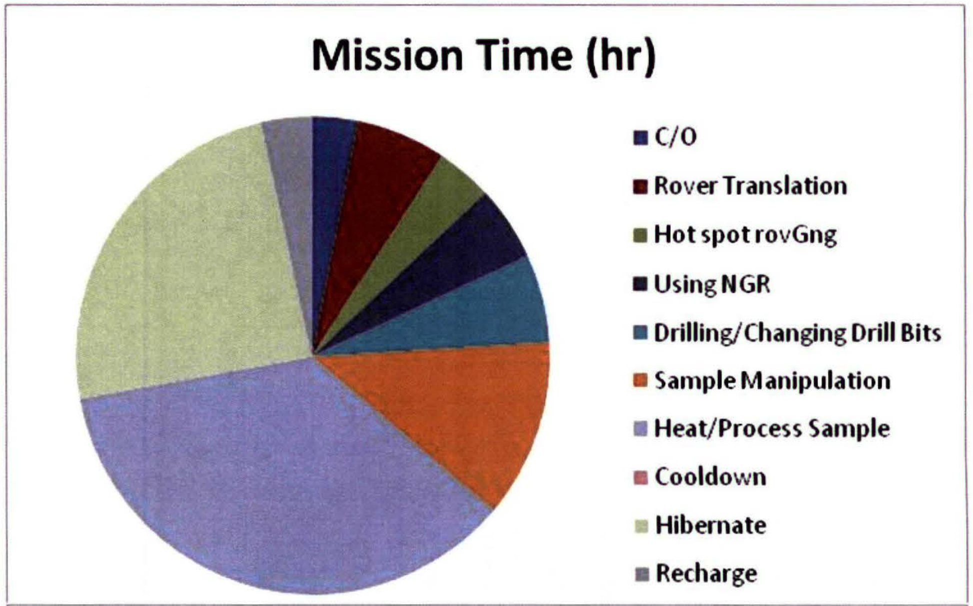
MISSION SUMMARY

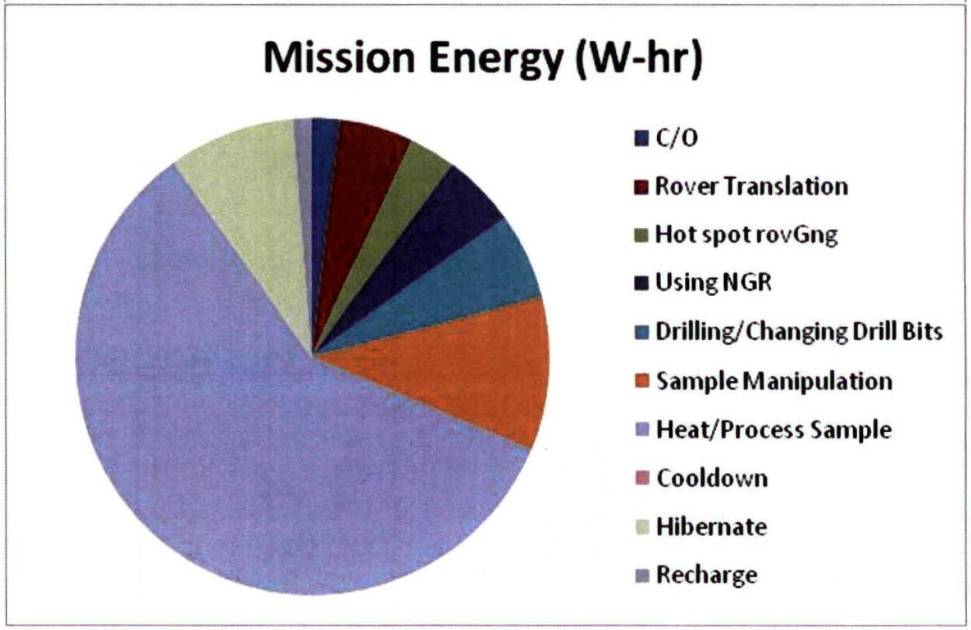
- Mission Length 9.5 days
  - 2.5 days Sun
  - 2.0 days Shadow
  - 5.0 days Sun
  - 8.2 days of Scheduled Activities
  - 1.3 days of Reserve Time
- Samples Processed
  - 25 processed at 150 deg C
  - 3 processed at 900 deg C
- Navigation
  - 5 navigation periods
  - Distance traveled is 3.0 km
- Drilling
  - Ten 0.5 m Augers
  - Five 1.0 m Cores

Time & Energy by Mission Function

2.5 days Sun, 2 days Shadow, 5 days Sun)

	time (hr)	energy (W-hr)
C/O	6.17	684.77
Rover Translation	11.90	1754.76
Hot spot rovGng	7.50	1105.50
Using NGR	10.00	1765.00
Drilling/Changing Drill Bits	11.65	2056.23
Sample Manipulation	24.01	3620.82
Heat/Process Sample	70.53	20603.69
Cooldown	0.00	0.00
Hibernate	48.00	3024.00
Recharge	6.81	429.21
sum (hrs)	196.57	35043.97
sum (days)	8.190567	





Time, Energy & Battery State of Charge by Segment
(2.5 days Sun, 2 days Shadow, 5 days Sun)

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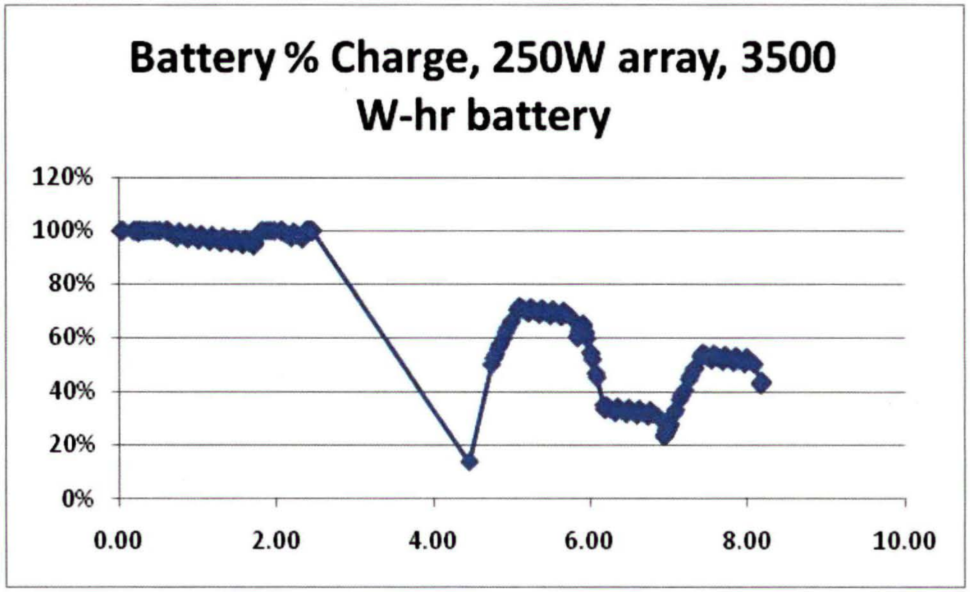
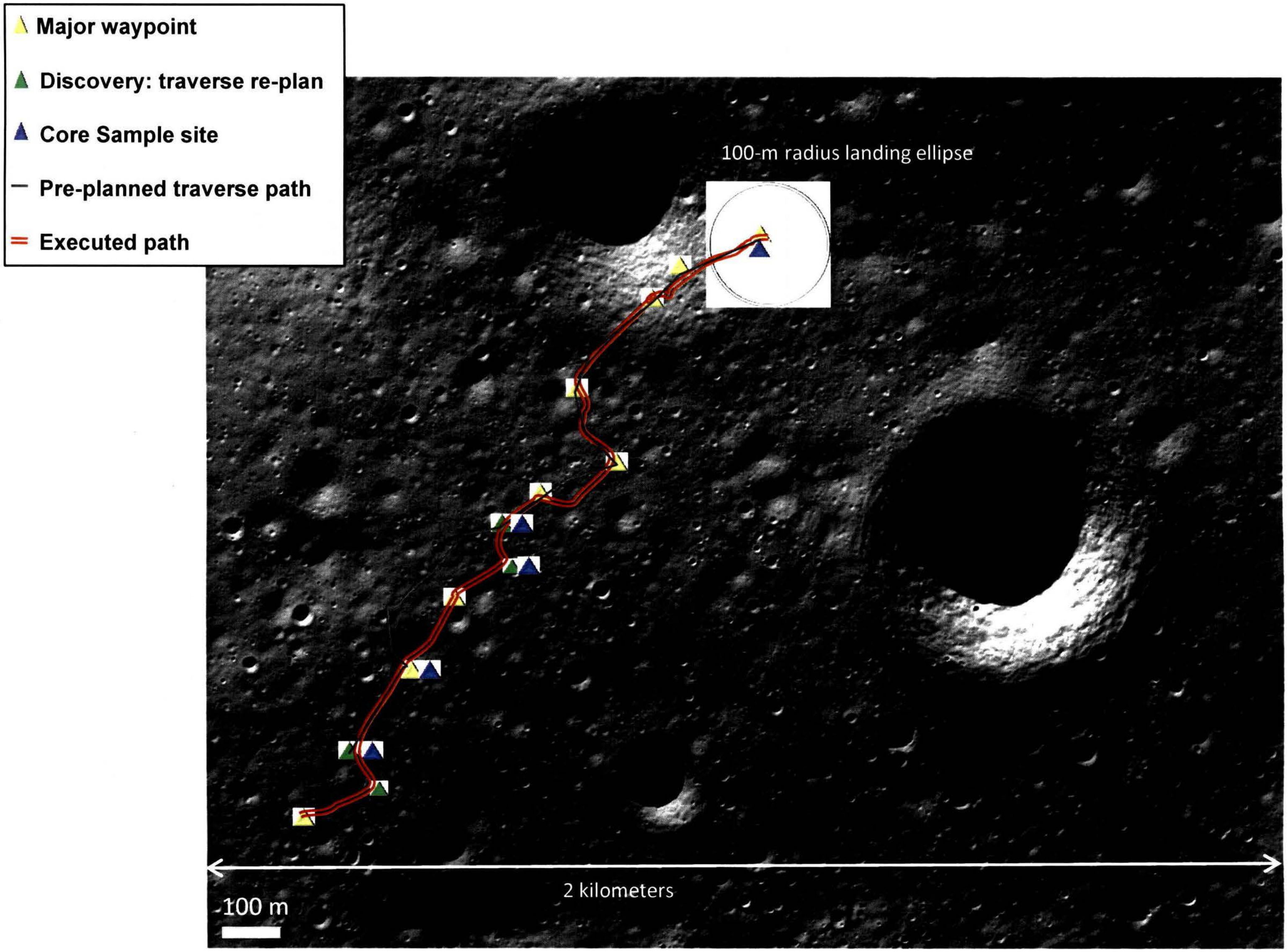
	time (hr)	energy (W-hr)
C/O	6.17	684.77
Nav 1	3.88	572.05
Drill 1	4.33	764.25
Process 1	26.84	6831.09
Nav 2	3.88	572.05
Drill 2	4.33	764.25
Process 2	9.59	2142.65
Hibernate + Recharge	54.81	3453.21
Nav 3	3.88	572.05
Drill 3	4.33	764.25
Process 3	19.85	5156.07
Nav 4	2.29	338.08
Drill 4	4.33	764.25
Process 4	19.85	5156.07
Nav 5	5.47	806.02
Drill 5	4.33	764.25
Process 5	18.41	4938.63
sum (hr)	196.57	35043.97
sum (days)	8.190567	



Notional Traverse Plan On Cabeus Floor



The Path Foward

- RESOLVE and Rover Ground Demonstration Units (GDU)have completed their 90% design reviews and fabrication has begun
- Flight software development is underway
- Ground Development Units were used to conduct a mission simulation at a Lunar Analog Site (Mauna Kea, Hawaii) in the Summer of 2012.
- Flight Test Unit design began in 2012 after initial integrated tests of RESOLVE GDU
- Goal is to have Flight Test Unit ready to go into thermal, vacuum and vibration testing.
- Hopefully, Commercial Lander capabilities will be coming on line in the 2014-15 timeframe due to the Google Lunar X-Prize.

"Sun&Shadow" Solar/Battery Rover Architecture

(Version 2.1, 2011-6-23)

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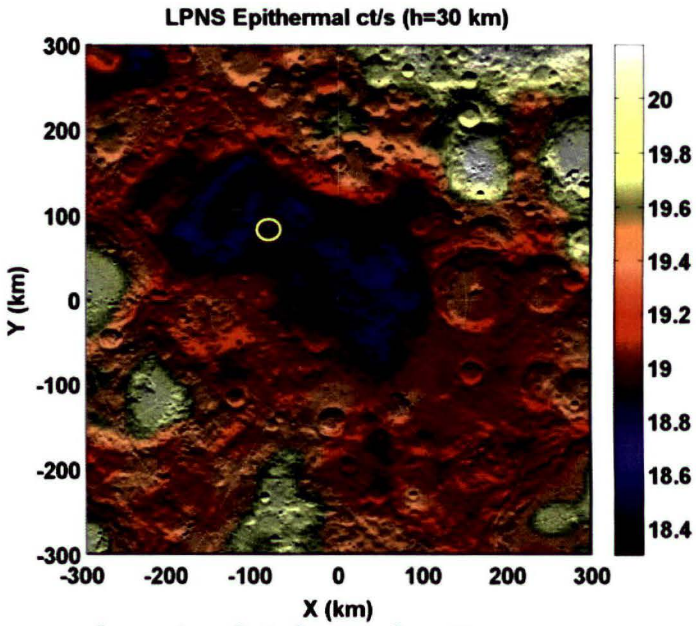
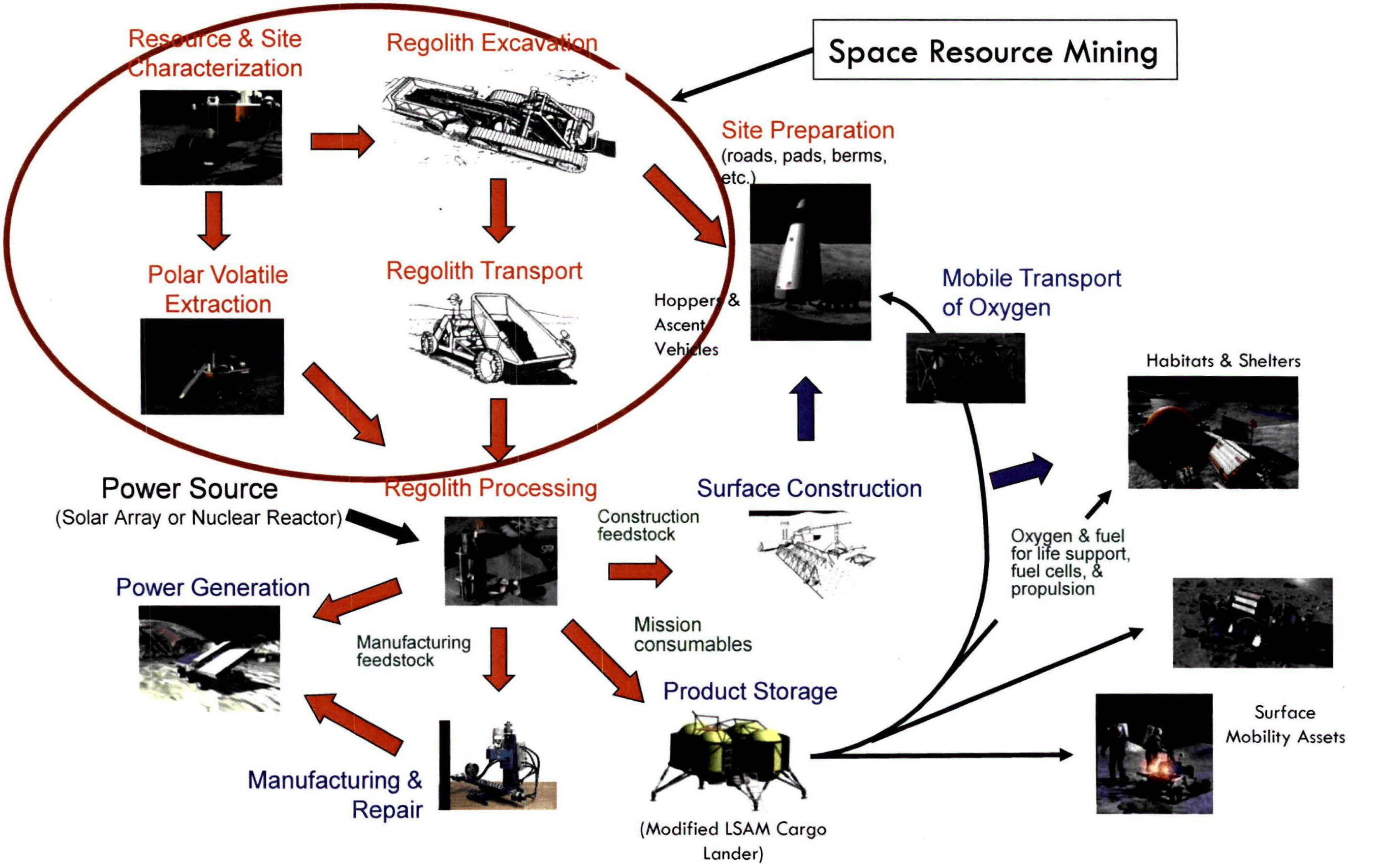
- **Destination:** **Moon South Pole**
- **Site:** **Cabeus A1**
  - Latitude: -85.75 deg
  - Longitude: -45 deg
- **Surface Mission Duration:** **9.5 days** (7.5 w/ sun)
- **Primary Spacecraft:** **Rover**
- **Power Strategy:** **Solar PV + Battery**
  - Solar Array: 250 We
  - Secondary Battery: 3500 W-hr
- **Comm. Strategy:** **Direct via McMurdo/Troll**
- **Survey Track:** **3,000 m**
- **Payload:**
  - Drill: 5x1m core, 10x0.5m auger
  - ISRU Reactor: 25@150C, 3@900C ISRU
  - Gas Chrom. / Mass Spec.: 25 samples
  - Neutron Spectrometer: 3000m
  - Near-IR Spectrometer: 3000m, 10 auger cuttings
- **Mission Energy:** **48,500 W-hr** available
- **Mission Ave. Power:** **178 W** predicted
- **Payload Mass:** **72 kg**
- **Rover+P/L Mass:** **243 kg**
- **Landed Mass:** **1285 kg**
- **Wet Mass @ TLI:** **3,476 kg**
- **Launch Vehicle Class:** **Atlas V 411**

Field Testing Rover Prototype



Cabeus South Pole Landing Site

Space Resource Life Cycle



Regolith vs. Volatiles

- Surface scooping of the regolith is the easiest way to obtain O_2 through Hydrogen Reduction (1% yield), Carbothermal Reduction (12-14% Yield) or Molten Regolith Electrolysis (28% Yield)
- Due to the stoichiometric ratio of H2 and O2 combustion, O2 is typically 85 % of the mass required for propulsion
- If we want to have a fuel as well (H2, CH4), then we must mine the volatiles, which only exist in thermally stables regions below the regolith or in lunar crater cold traps at the poles.
- Thermal models have shown that there may be water ice present in areas surrounding the craters at depths below 30 cm

- **Mining robots must be able to scoop surface regolith for O_2 ISRU**

- **Mining Robots must be able to dig below 30 cm for Volatiles ISRU including H_2O and CH_4**

Lunar Regolith Compaction

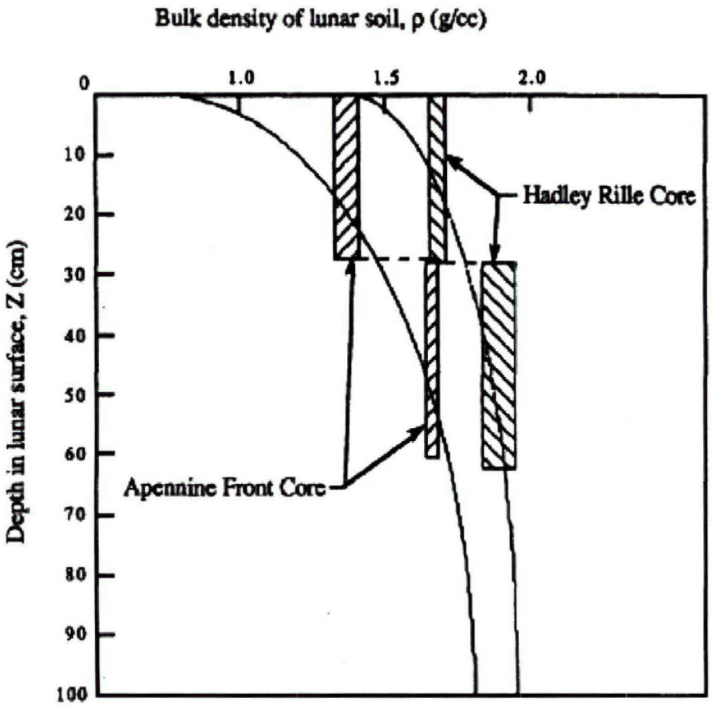


Figure 1. VARIATION OF LUNAR REGOLITH BULK DENSITY WITH DEPTH. The sectioned areas show the actual density variations and the smooth lines show the curve-fit given by Equation 1.[9]

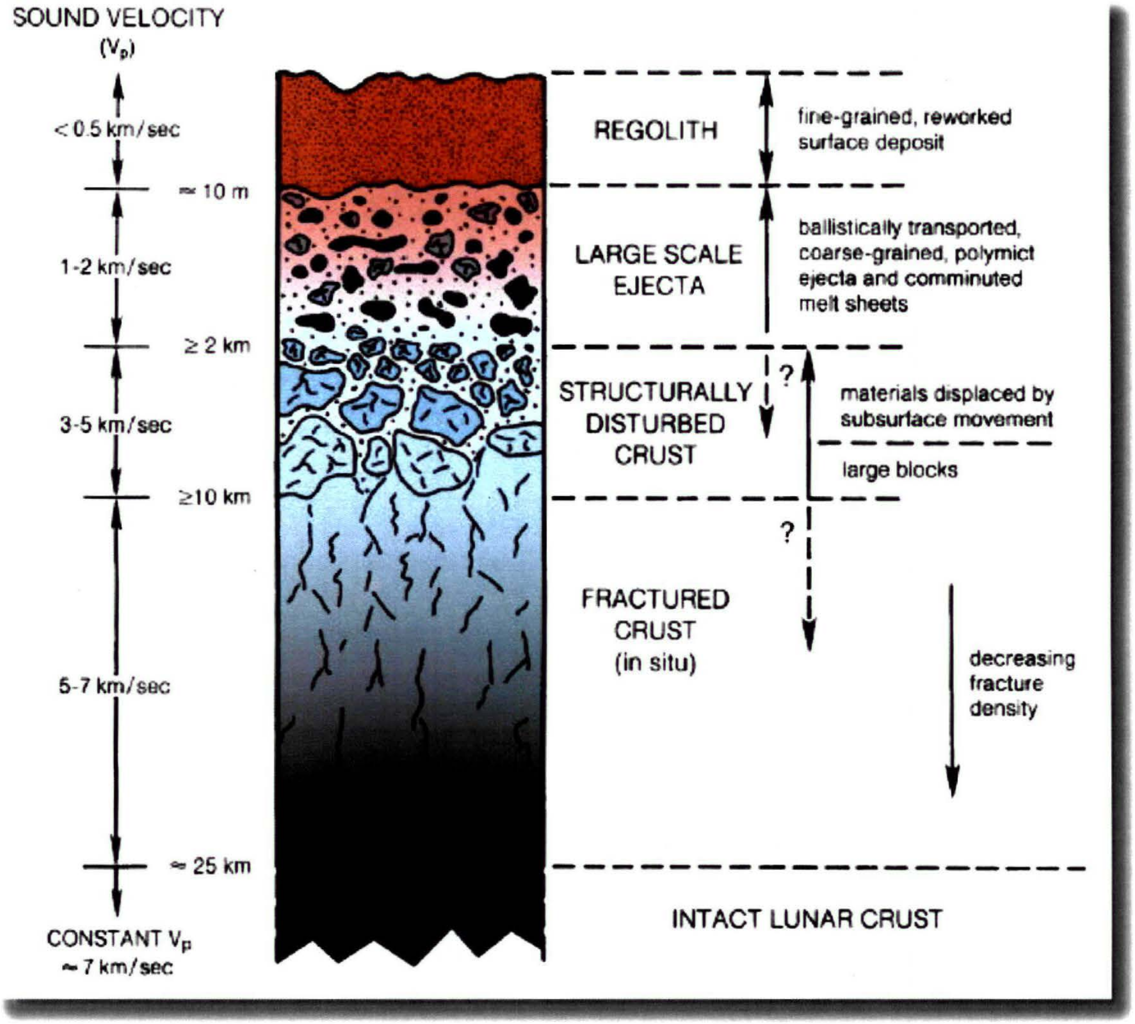
8. Mitchell, J.K., et. al., "Mechanical Properties of Lunar Soil: Density, Porosity, Cohesion, and Angle of Internal Friction", Proceeding of the Third Lunar Science Conference, Vol. 3, Criswell, David R., ed.(MIT Press: Cambridge, MA, 1972), p. 3242.

Regolith Densities (Lunar Sourcebook, LPI)

Very Loose	1.15 g/cm^3 – 1.22 g/cm^3
Loose	1.22 g/cm^3 – 1.32 g/cm^3
Medium	1.32 g/cm^3 – 1.51 g/cm^3
Dense	1.51 g/cm^3 – 1.68 g/cm^3
Very Dense	1.68 g/cm^3 – 1.82 g/cm^3

The top 25-30 cm of Lunar Regolith are Loose, below that is harder to excavate and mine

Lunar Regolith Model

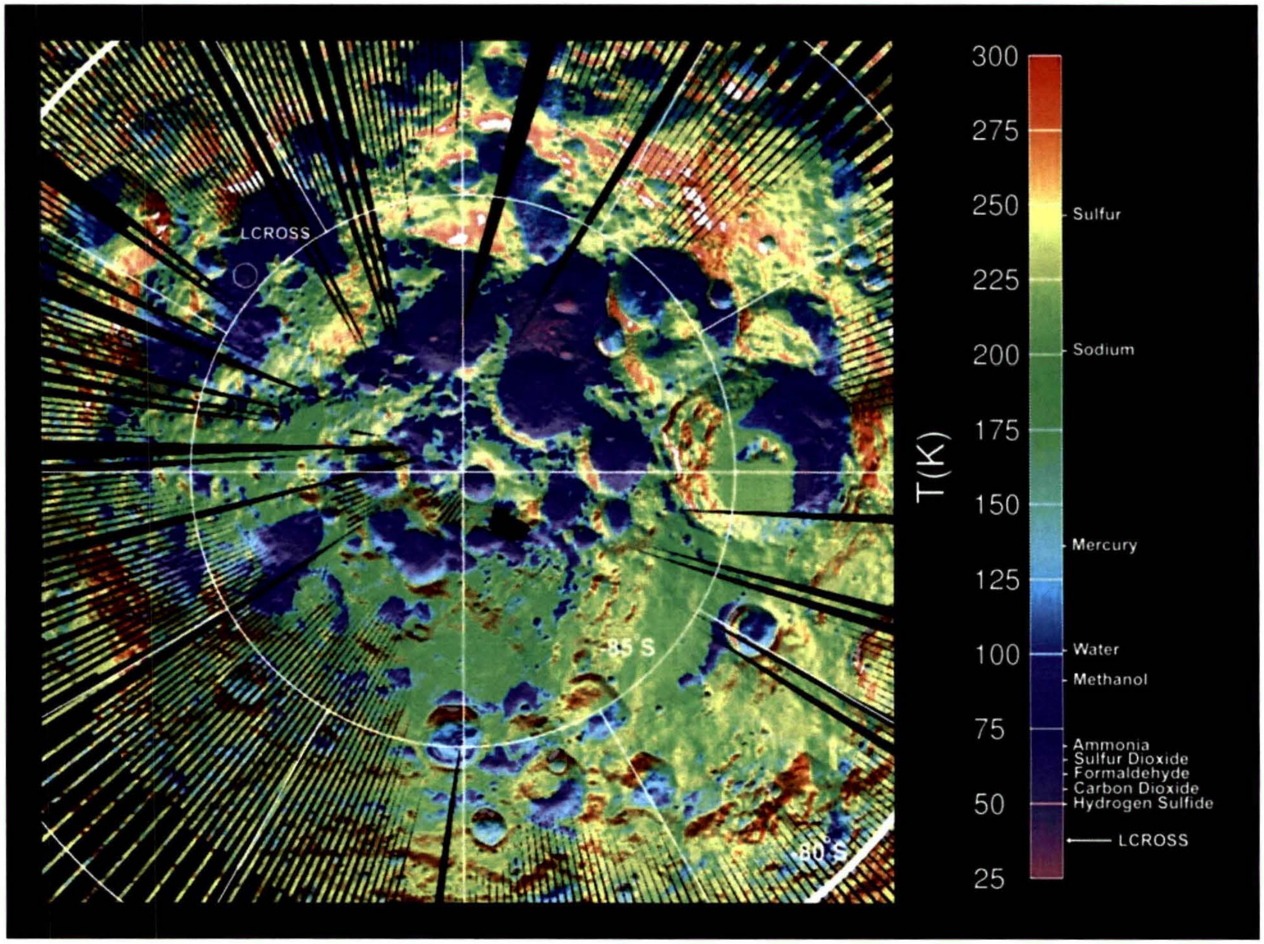


The top 10 m of Lunar Regolith are fine grained

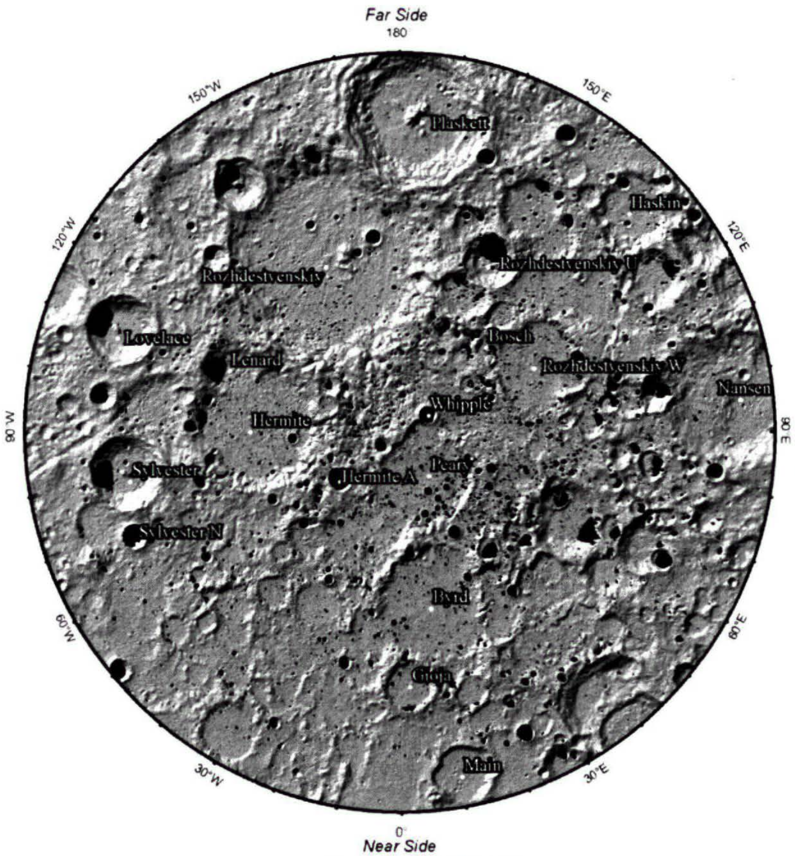
Source: Jeff Plescia of JHU-APL. "2nd Workshop on Granular Materials in Lunar & Martian Exploration", ASCE Earth & Space 2006 Conference March 5-8, 2006 in Houston, TX

PSR Definition & Options

The moon's axis of rotation is nearly perpendicular to the plane of its orbit around the sun, which casts long shadows off of crater rims and creates areas that never receive sunlight. These permanently shadowed regions (PSRs) have temperatures reaching below 90 K. At these temperatures, volatiles (including sulfur, carbon, hydrogen, hydrocarbons, and water ice) are stable there indefinitely.



PSRs Map



NORTH POLE > 80°

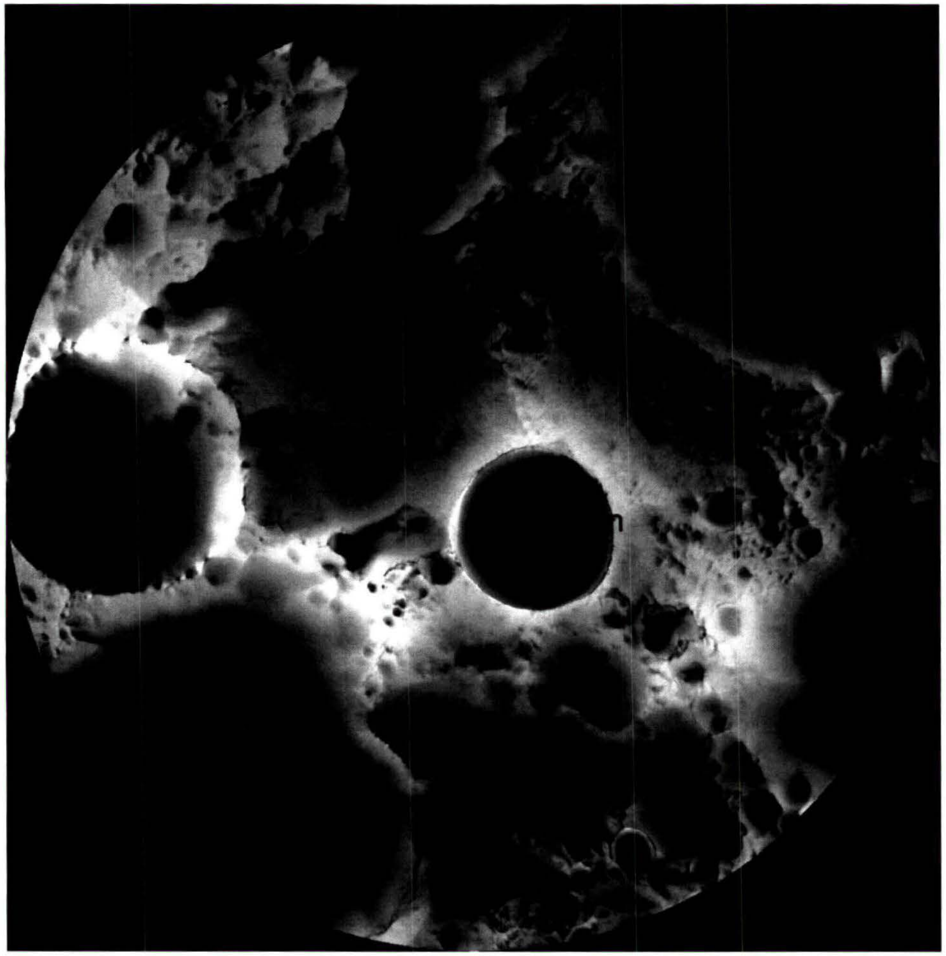
SOUTH POLE < -80°

Legend

Permanently Shadowed Regions

SOURCE: LUNAR AND PLANETARY INSTITUTE, HOUSTON, 2011

PSRs – Shackleton Crater



SOUTH POLE ILLUMINATION MAP
AREA EXTENDS FROM 88°S TO 90°S [NASA/GSFC/ ARIZONA STATE UNIV].

- Located at south pole
- 19-km diameter
- LRO data suggests up to 22% surface content is water ice
- Rim areas in sunlight most of the year
- Interior entirely in permanent shadow
- Rugged interior and steep walls

PSRs – Shackleton Crater

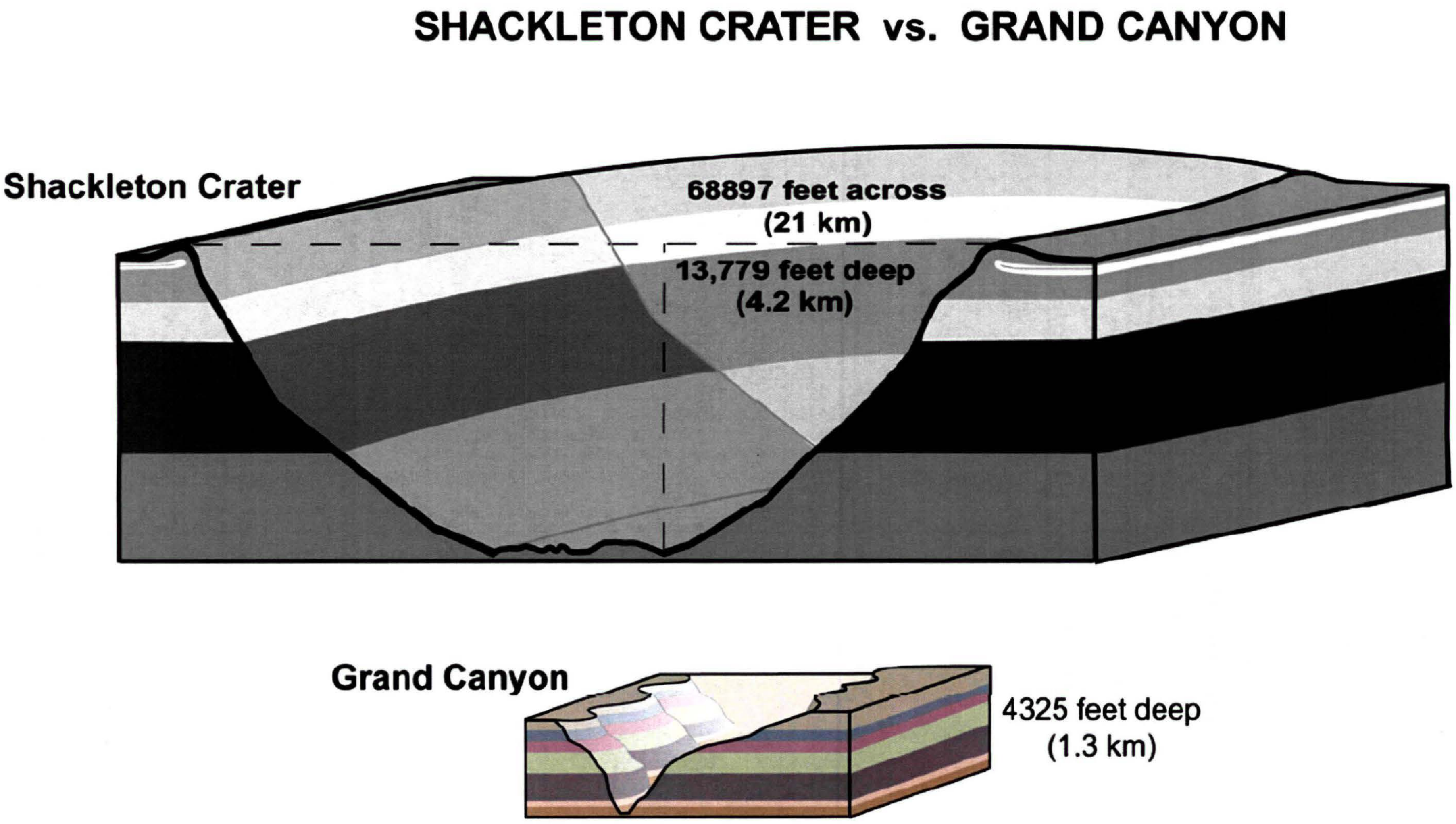
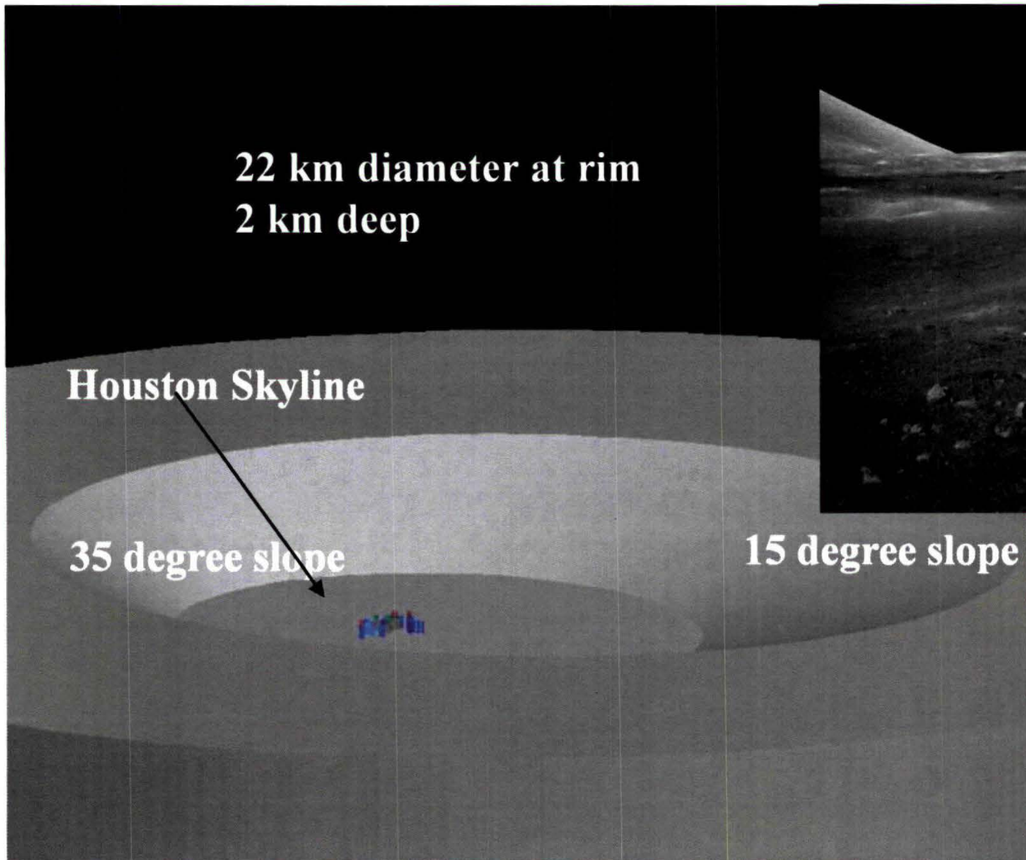


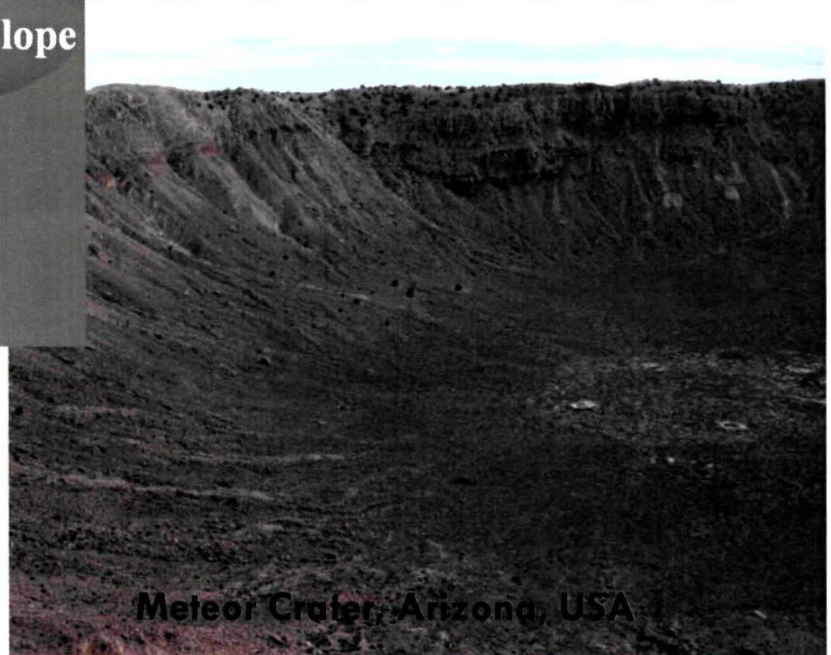
IMAGE CREDIT: DR. DAVID KRING (USRA)

Extreme Access Required

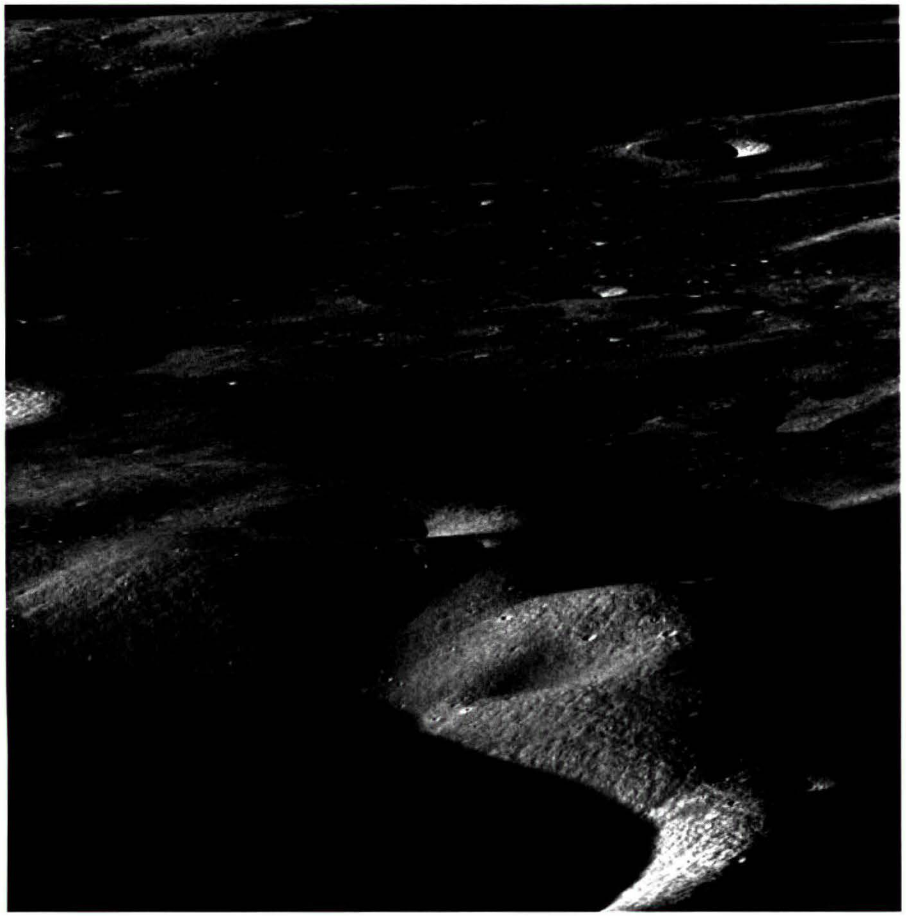


Credit: Jerry Sanders, NASA JSC

Credit: MER Rover Opportunity, NASA JPL

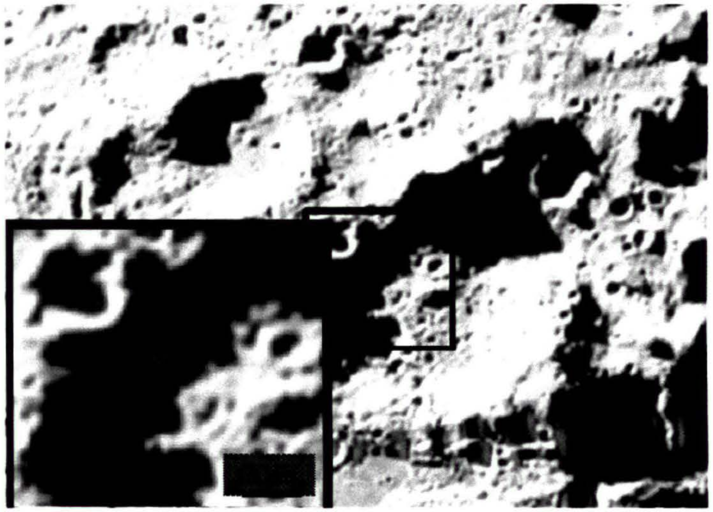


PSRs – Cabeus Crater



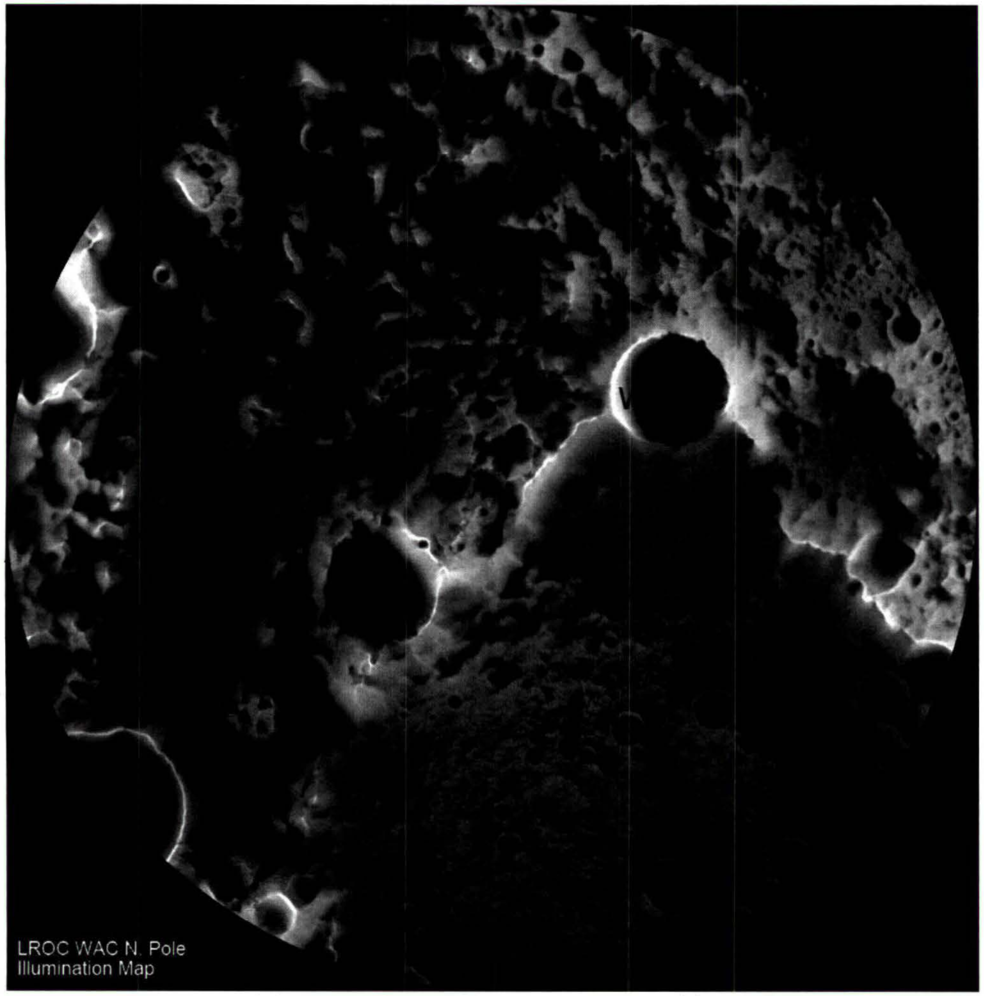
Overview of a portion of the Cabeus northern rim looking from the southwest. Credit: NASA/GSFC/AZ State Univ.

- ~100-km diameter
- Site of LCROSS Centaur impact
- Significant areas of permanent shadow
- Estimated 5.6 mass% water ice



LCROSS Impact

PSRs – Small Craters



NORTH POLE ILLUMINATION MAP
AREA EXTENDS FROM 88°S TO 90°N [NASA/GSFC/ARIZONA STATE UNIV.]

- Hundreds of small (<15 km) craters with PSRs within 12 degrees of poles [Bussey et al., 2003]
- Mini-SAR instrument imaged 40 small craters with water ice, ranging in size from 2 to 15 km
  - Contain estimated 600 million metric tons of water ice

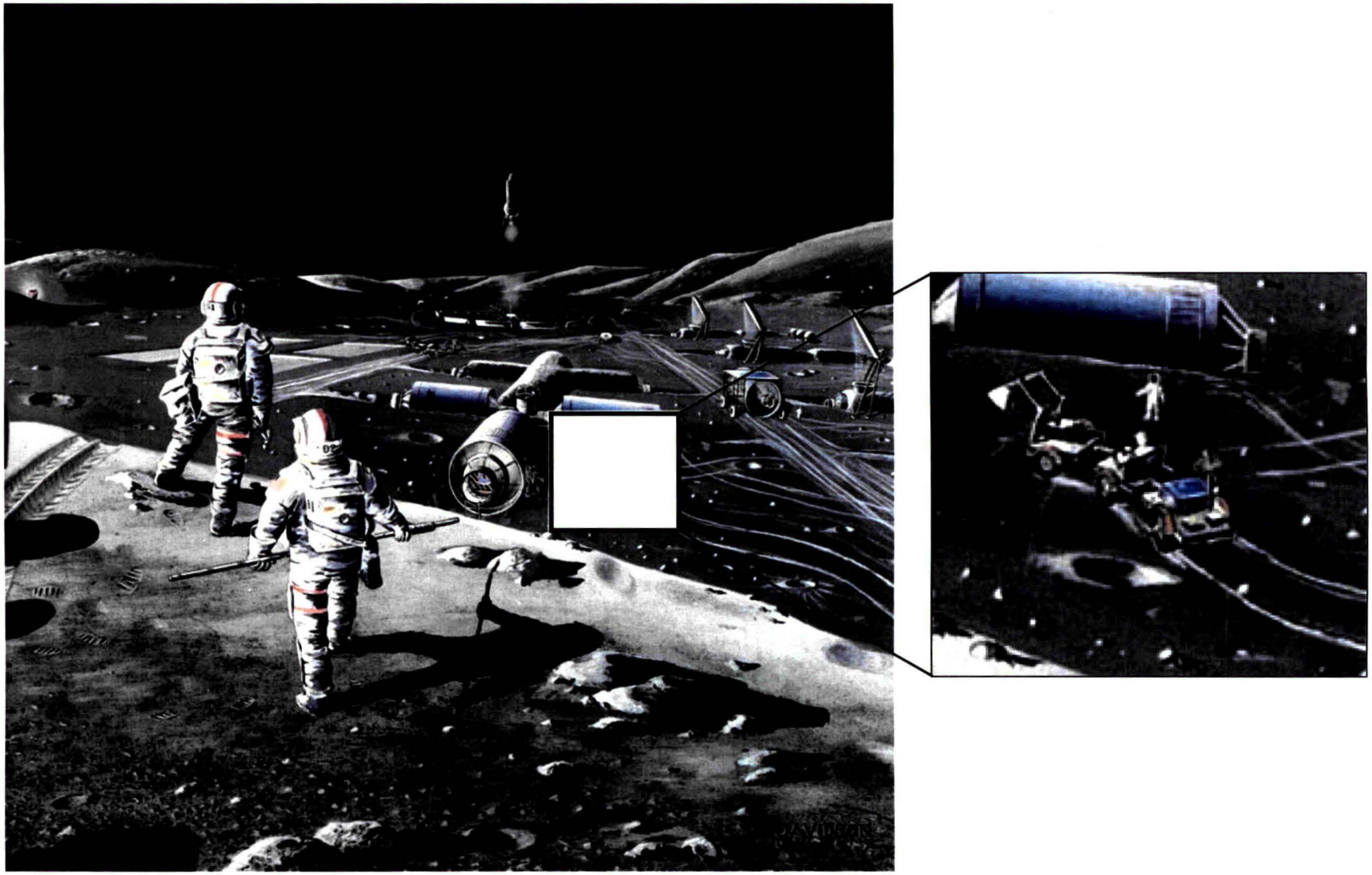
Take Away Points

- Solar System Resource Utilization is the key to expanding Civilization off Earth
- The Solar System has vast amounts of resources but they must be acquired and processed to be useful
- Asteroids have huge amounts of resources in the Asteroid Belt and NEA's
- Lunar Poles are also showing remote sensing evidence of volatiles resources
- Accessing the PSR craters is extremely hard and harsh – survival is challenging
- New Technologies and methods are required

Terrestrial Robotic Mining

- Increased safety and improved working conditions for personnel
- Improved utilization by allowing continuous operation during shift changes
- Improved productivity through real-time monitoring and control of production loading and hauling processes
- Improved draw control through accurate execution of the production plan and collection of production data
- Lower maintenance costs through smooth operation of equipment and reduced damage
- Remote tele-operation of equipment in extreme environments
- Deeper mining operations with automated equipment
- Lower operation costs through reduced operating labor
- Reduced transportation and logistics costs for personnel at remote locations
- Control of multiple machines by one tele-operator human supervisor

Early Visionary Studies 1900- 1980's



Eagle Engineering Reports -1988

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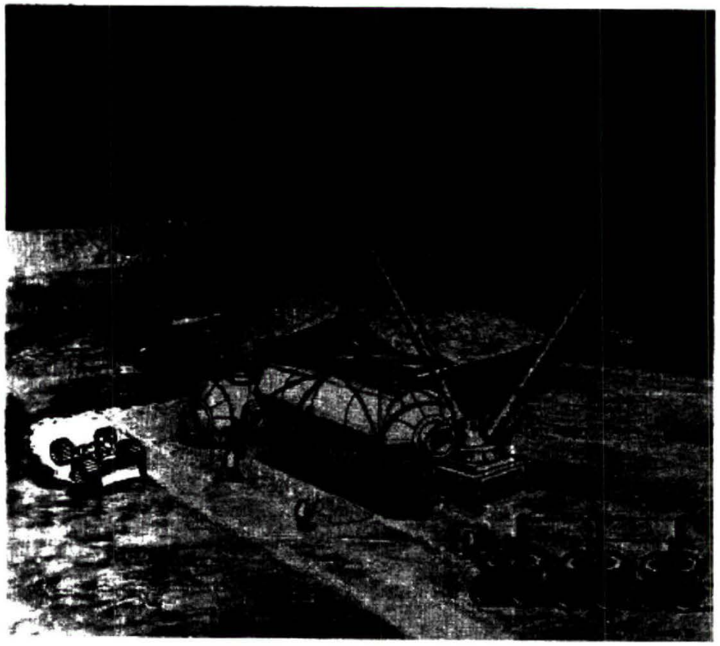
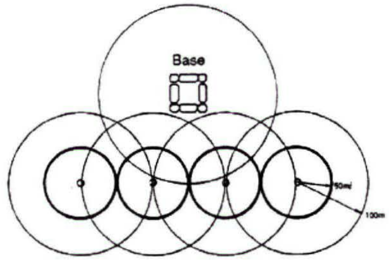
LBSS
Lunar Surface Construction & Assembly Equipment Study



EEI Report Number 88-194
NASA Contract Number NAS 9-17878
1 September, 1988

EAGLE

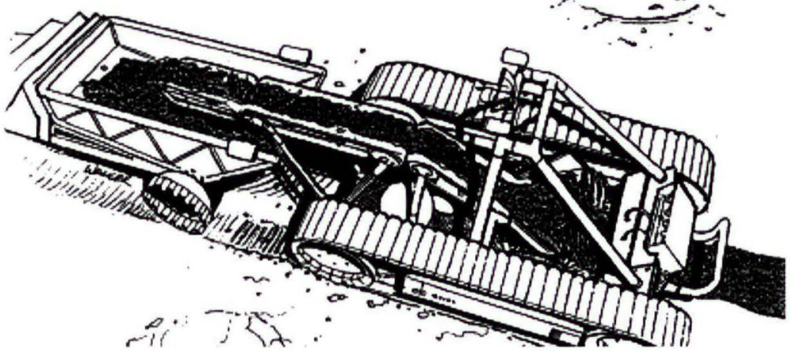


Lunar Base Launch and Landing Facility Conceptual Design

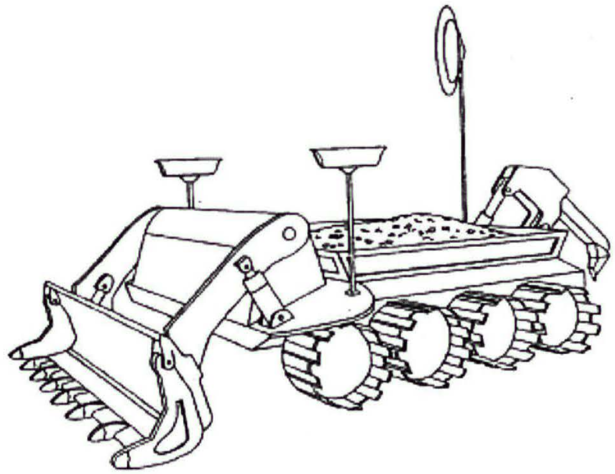
NASA Contract Number NAS9-17878
EEI Report 88-178

EAGLE

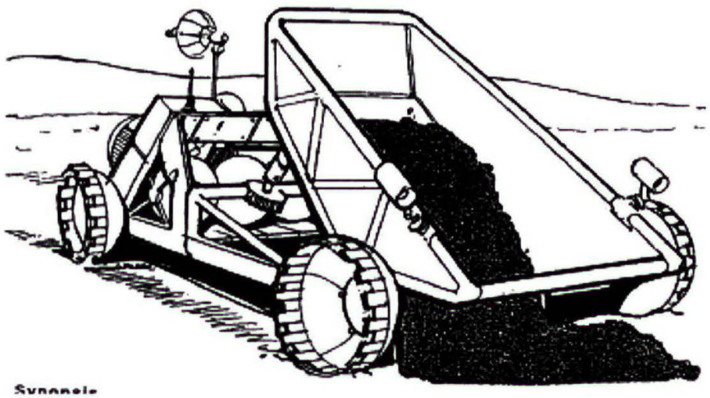
Mining Excavator/Loader, Lunar



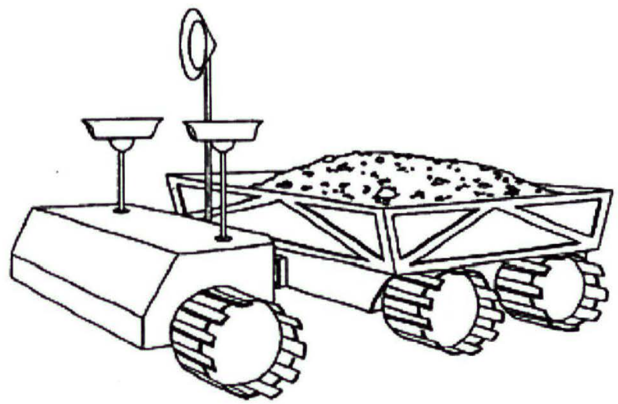
Ripper/Excavator/Loader



Regolith Hauler, Lunar

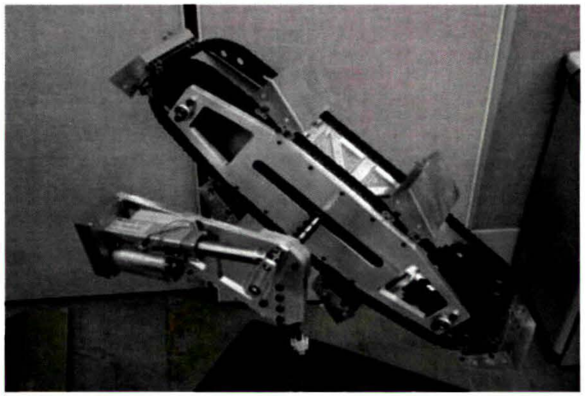


Articulated Hauler



Colorado School of Mines 2001 - 2011

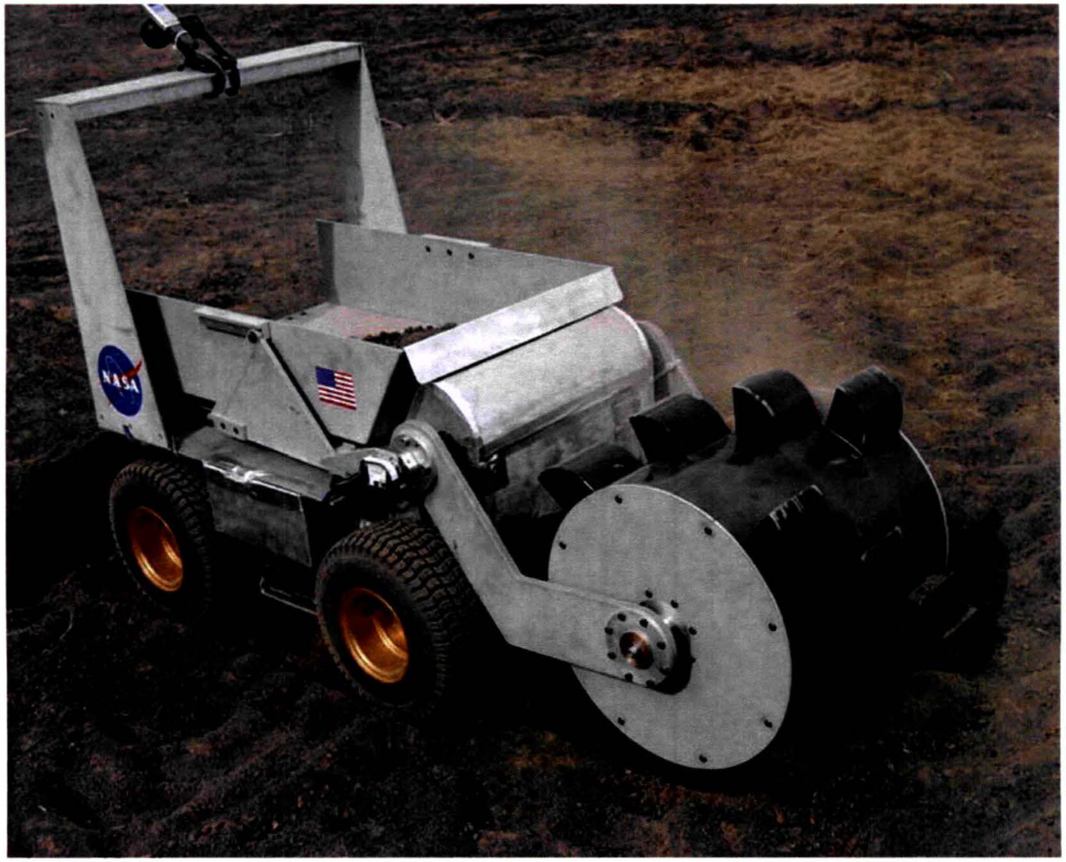
Mike Duke Project



Paul van Susante Projects

SysRand NASA SBIR

Lockheed Martin Bucket Drum - 2008



Lockheed Martin Corp. Bucket Drum Excavator (BDE) prototype.

NASA Centennial Challenge
Regolith Excavation Competition 2007-2009

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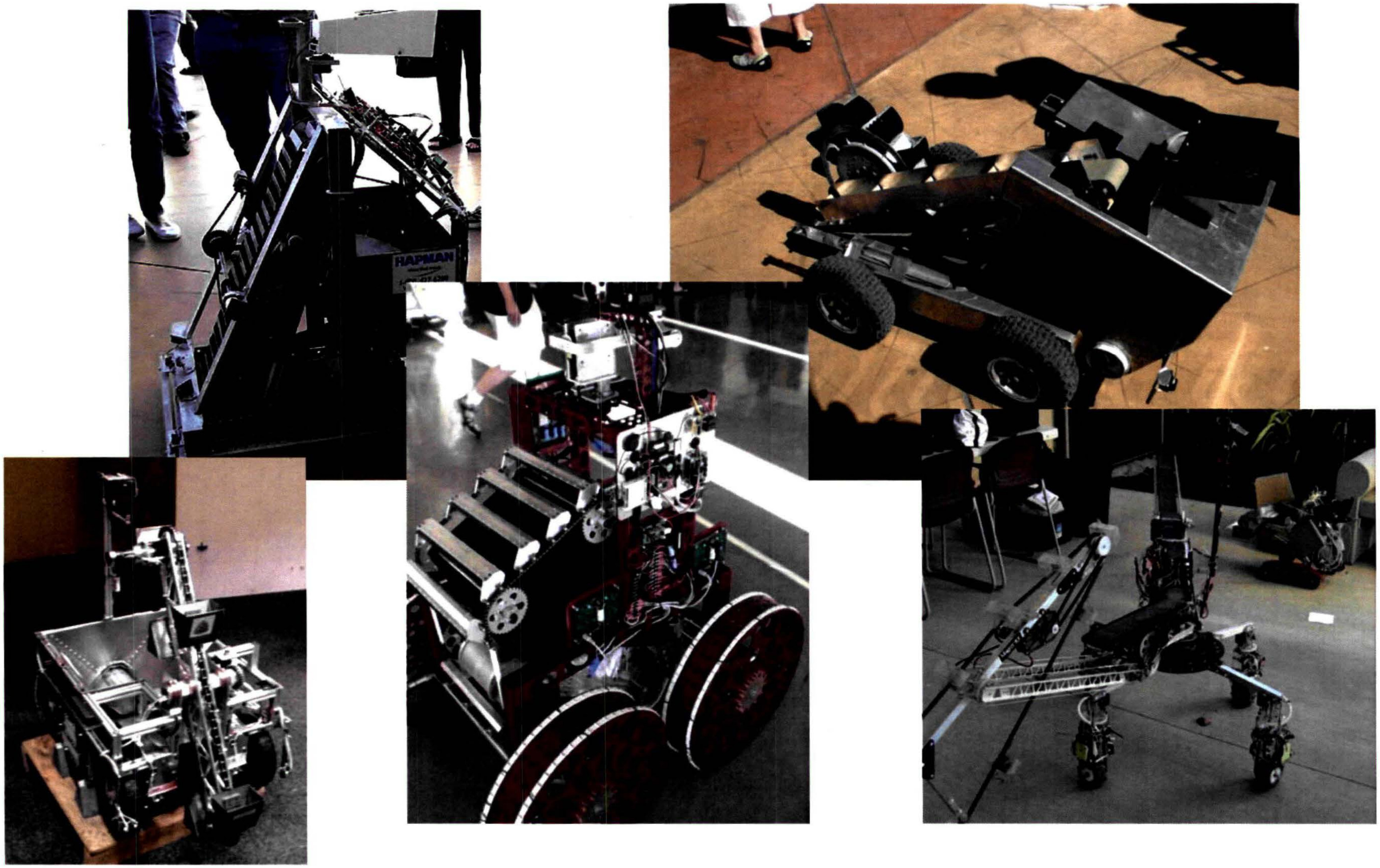
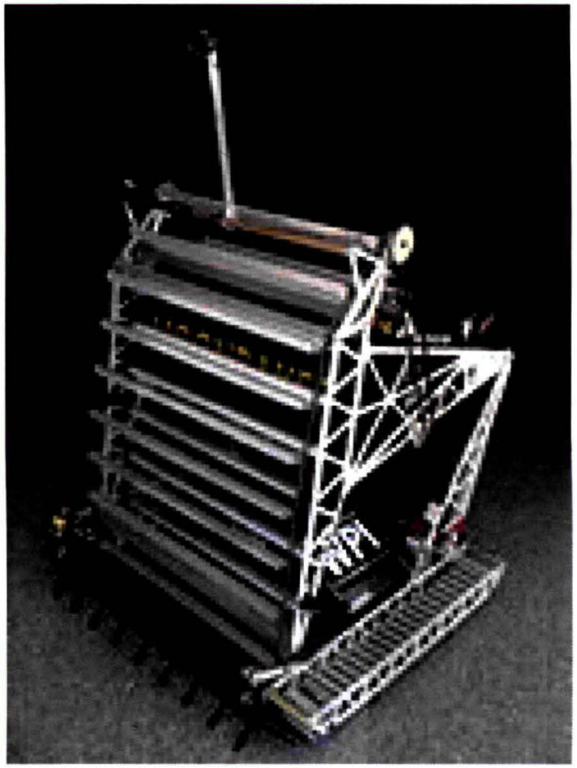


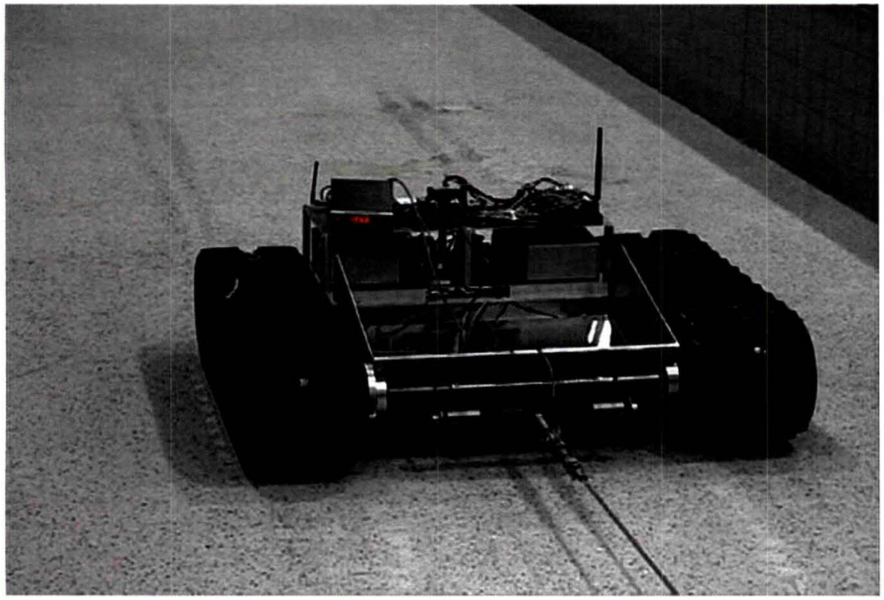
NASA Centennial Challenge
Regolith Excavation Competition Winner 2009

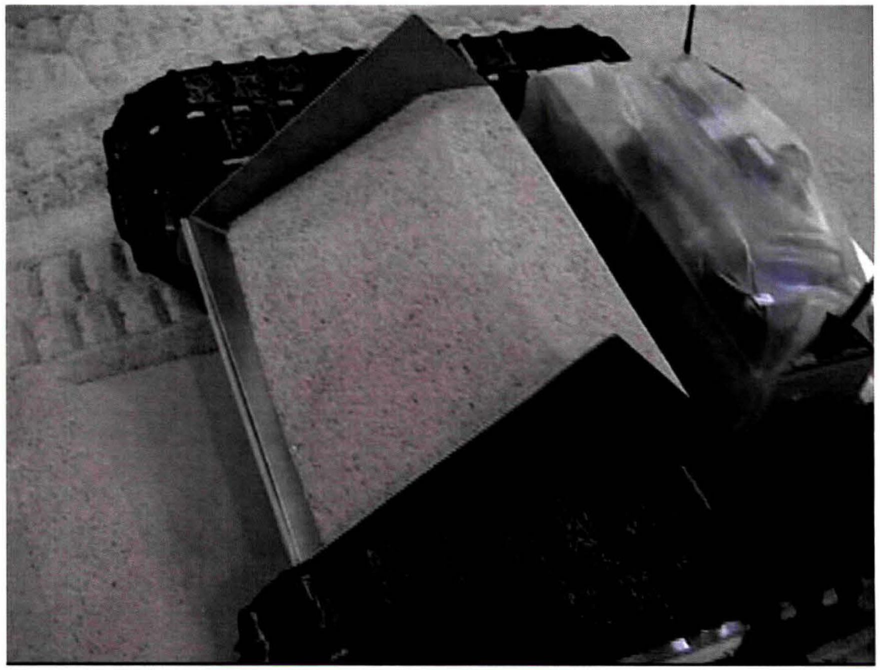
Paul's Robotics Centennial Challenges Winner,
Worcester Polytechnic Institute (WPI),
Worcester, Massachusetts



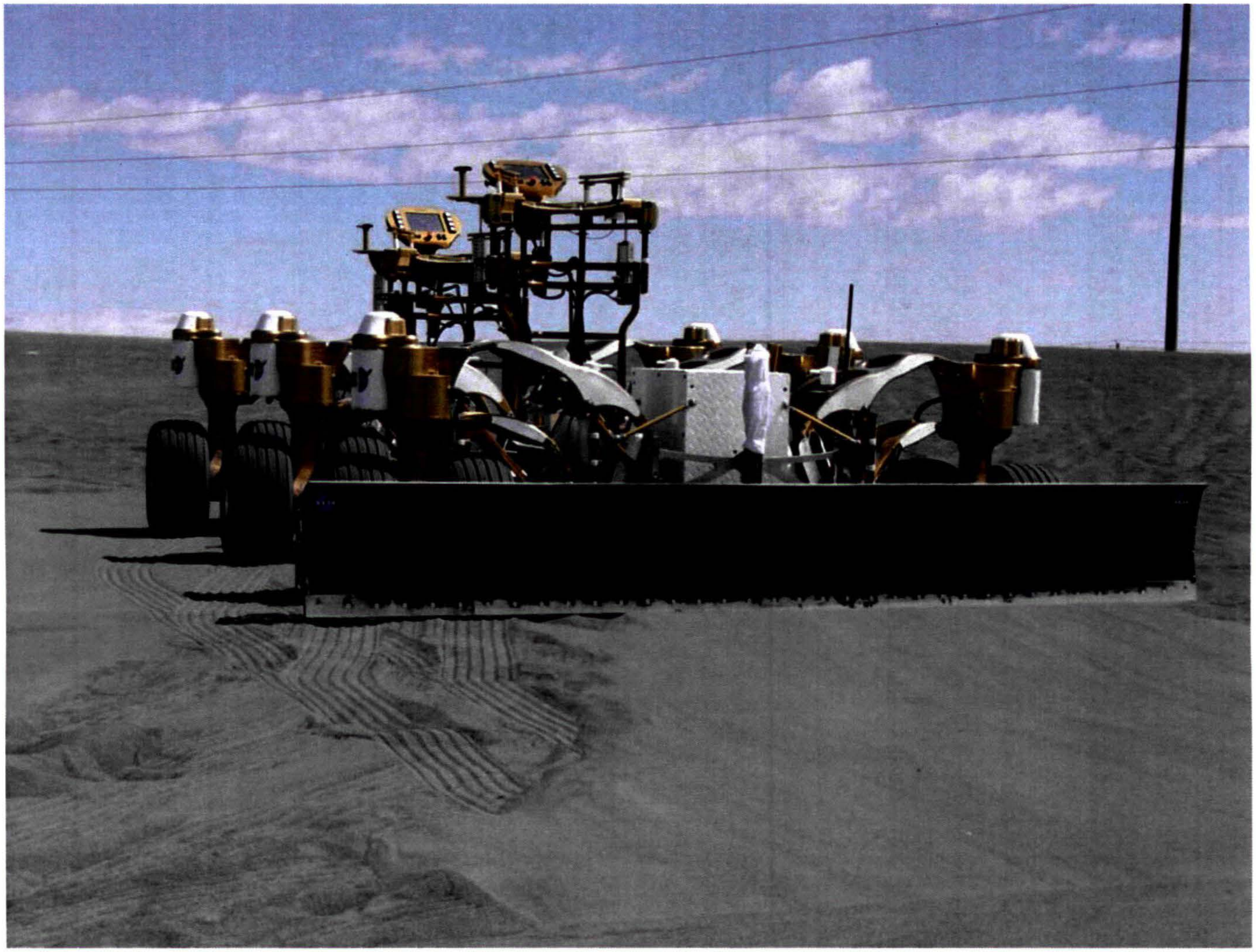
$500,000 Prize !

NASA Cratos – 2007
Glenn Research Center

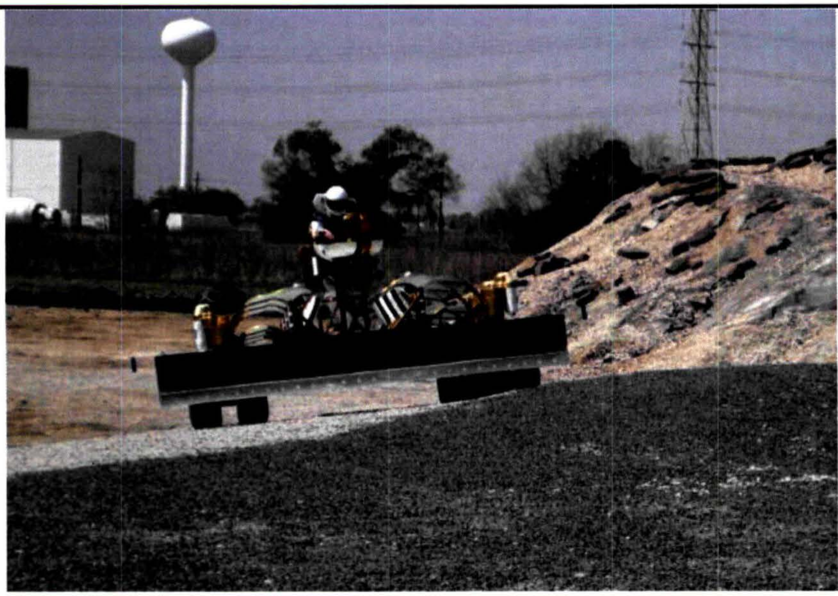


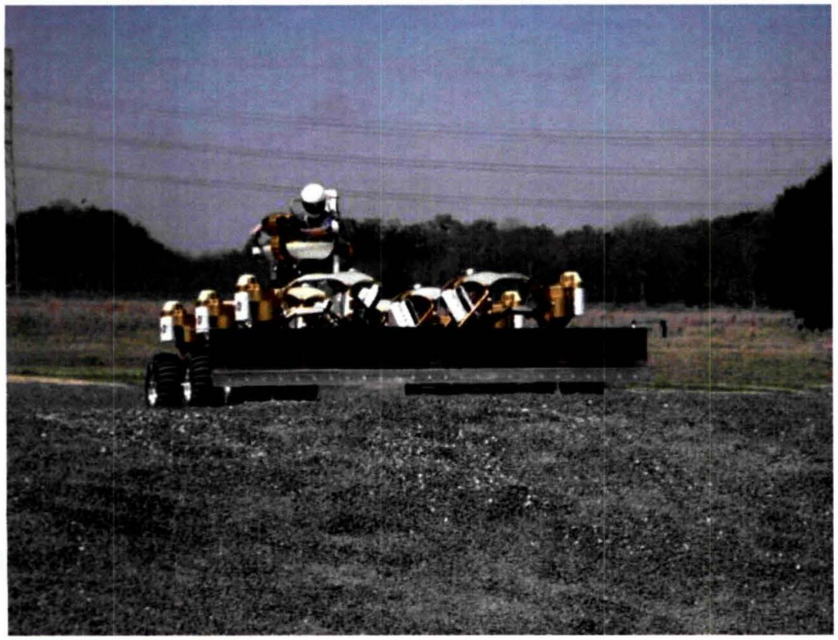


Lunar Attachment Node for Construction & Excavation (LANCE) on Chariot – NASA JSC/KSC 2009

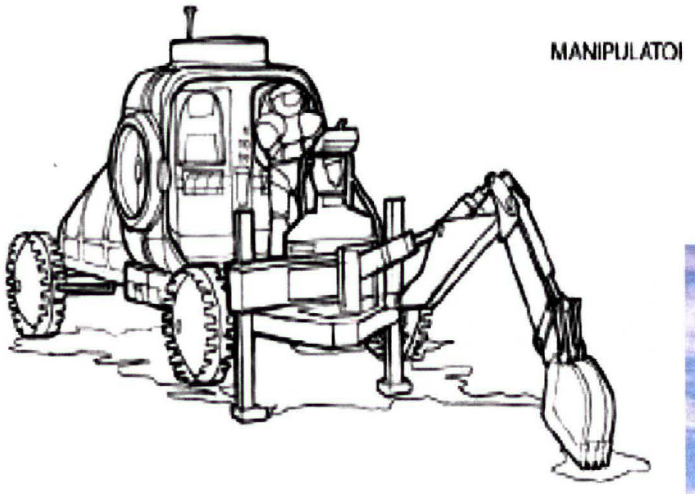


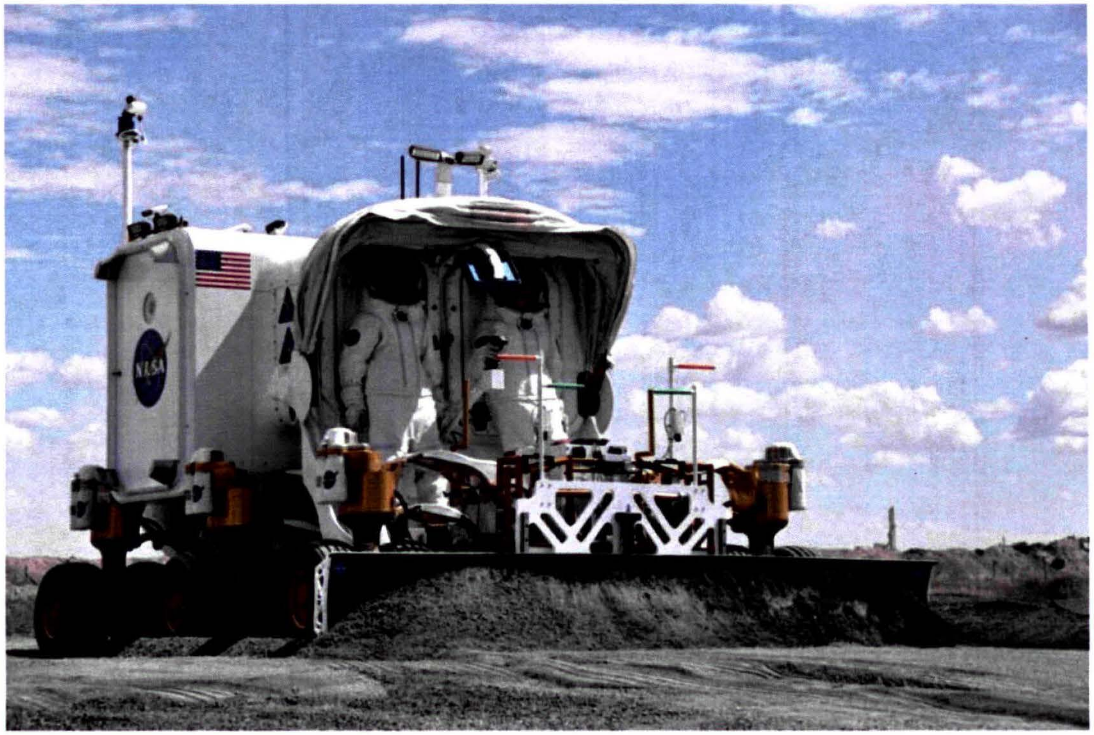
Lunar Attachment Node for Construction & Excavation (LANCE) on Chariot – NASA 2009





Space Exploration Vehicle (SEV) 2010-2012



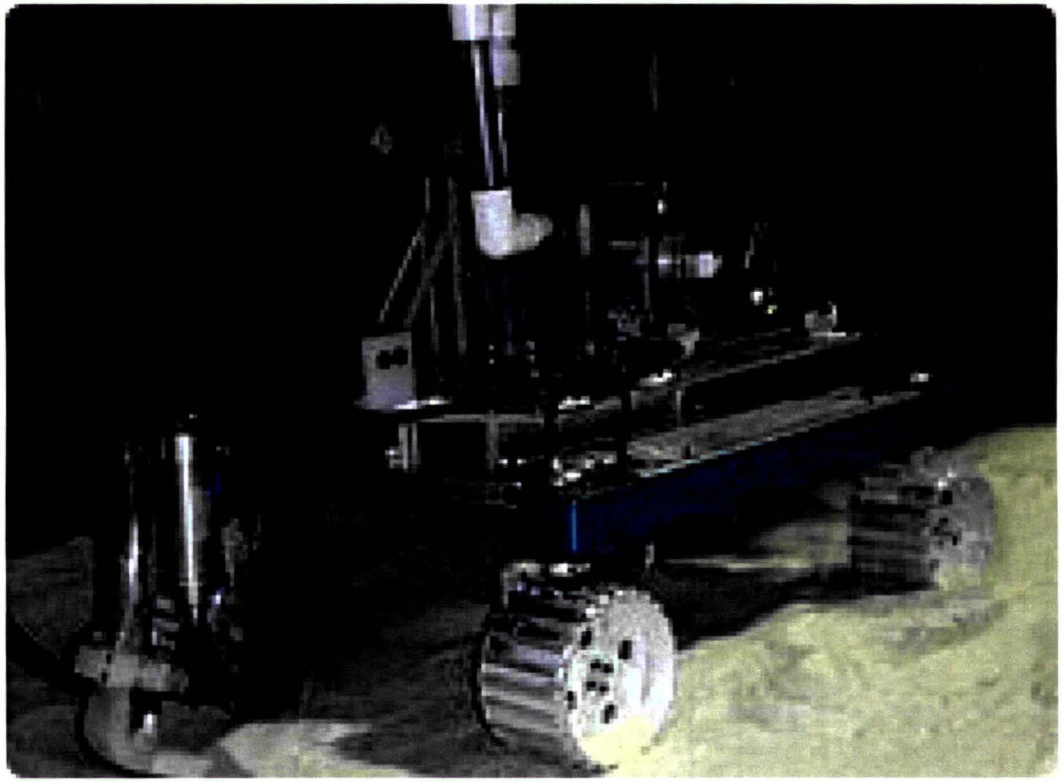


ATHLETE Excavation, NASA JPL : 2009 - 2011

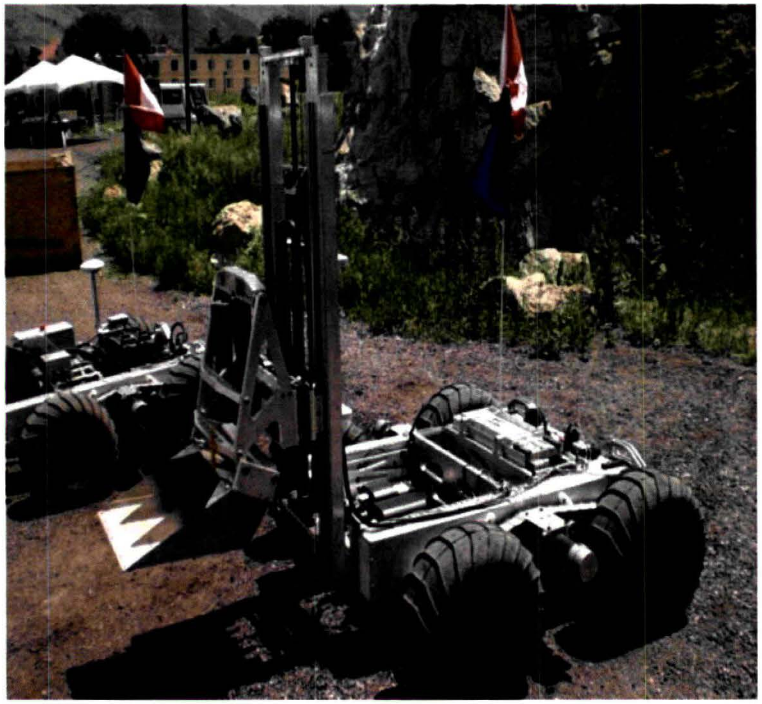
Caterpillar 287C semi-autonomous Multi Terrain Loader

JSC/GRC/KSC – 2010-2011

Pneumatic Excavation and Regolith Transport
Honeybee Robotics and NASA KSC: 2009-2011

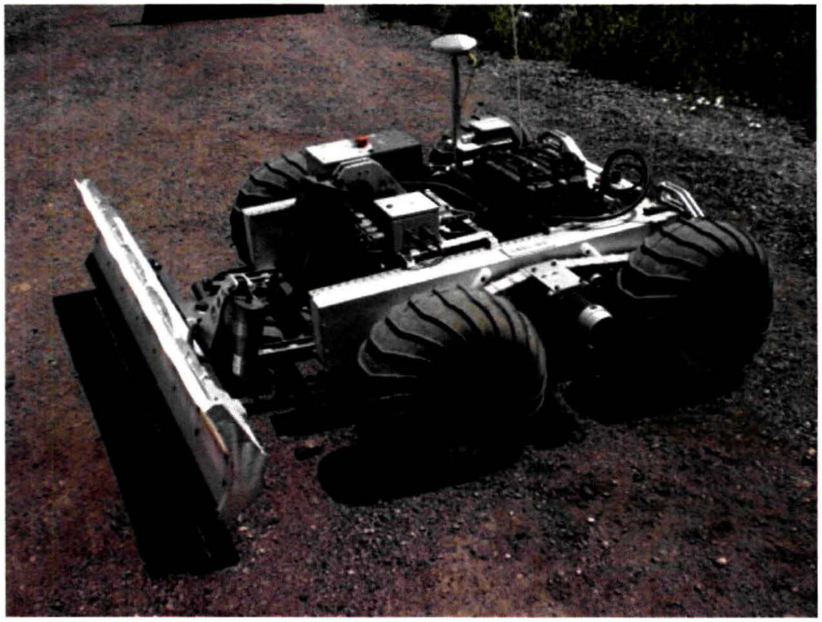


Canadian Space Agency, 2010 Mauna Kea ISRU Tests (NORCAT & Juno NEPTEC Rover)

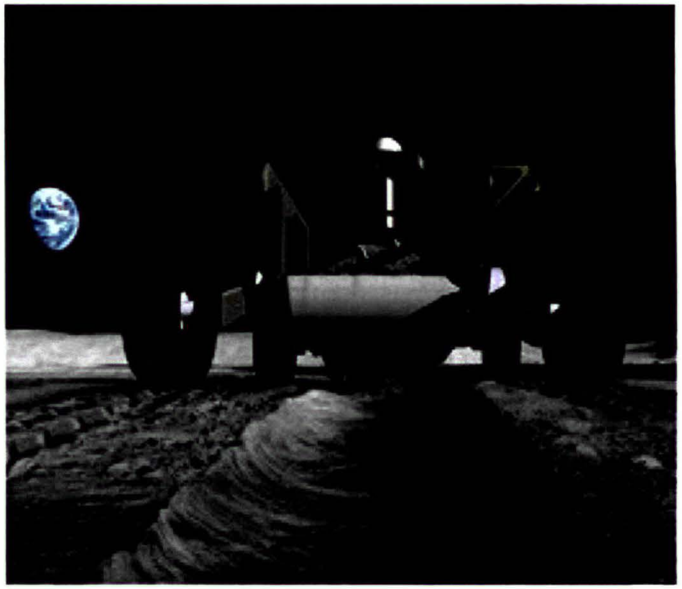


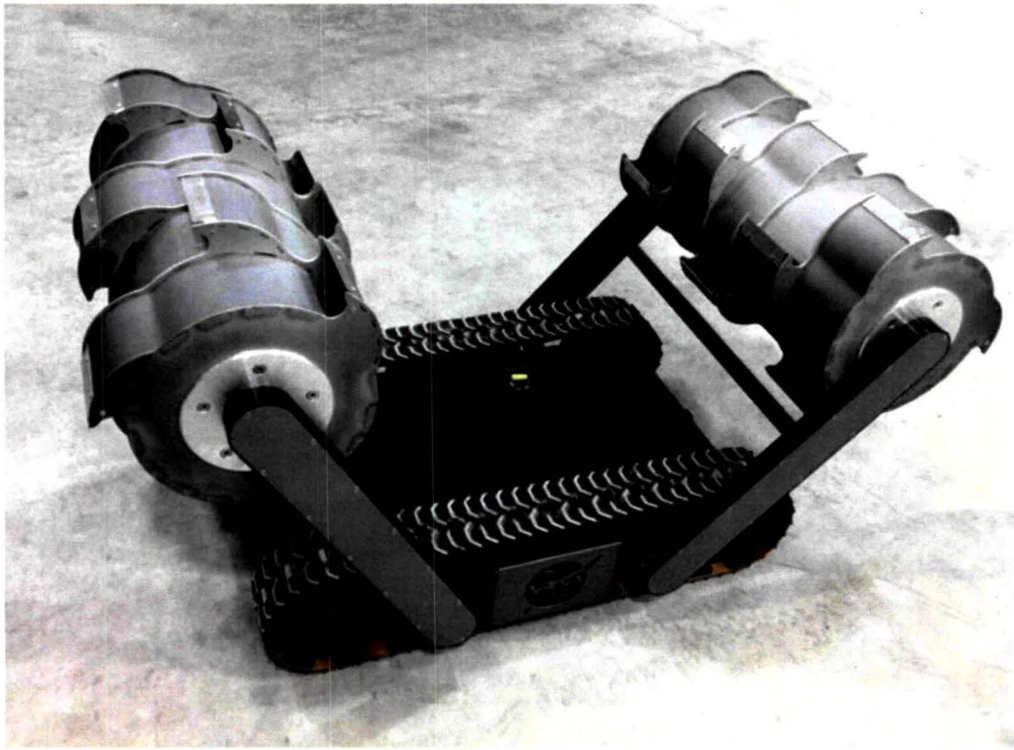
Load, Haul, Dump Excavator

Small Bulldozer



Astrobotic Technology inc. Lunar Mining Concepts
NASA SBIR 2010-2012





NASA Kennedy Space Center Excavator.
Regolith Advanced Surface Systems Operations Robot (RASSOR)

Held Annually since 2010

Regolith Excavation Mechanisms

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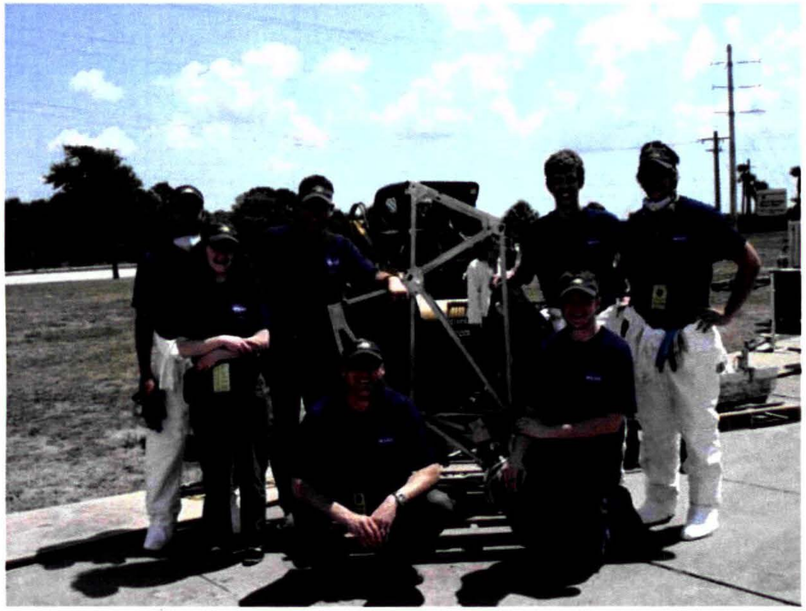
All excavators from three Centennial Excavation Challenge Competitions (2007, 2008 and 2009) and Lunabotics Mining Competitions (2010, 2011 & 2012)

Regolith Excavation Mechanism	# of machines employing excavation mechanism	Lunabotics 2012
Bucket ladder (two chains)	29	10
Bucket belt	10	6
Front End Loader	10	14
Scraper	8	8
Auger plus conveyor belt / impeller	4	3
Backhoe	4	0
Bucket ladder (one chain)	4	1
Bucket wheel	4	2
Bucket drum	3	4
Claw / gripper scoop	2	0
Drums with metal plates or brush (street sweeper)	2	1
Bucket ladder (four chains)	1	0
Magnetic wheels with scraper	1	0
Rotating tube/scoops entrance	1	1
Vertical auger	1	0
Rotating Scoop		1

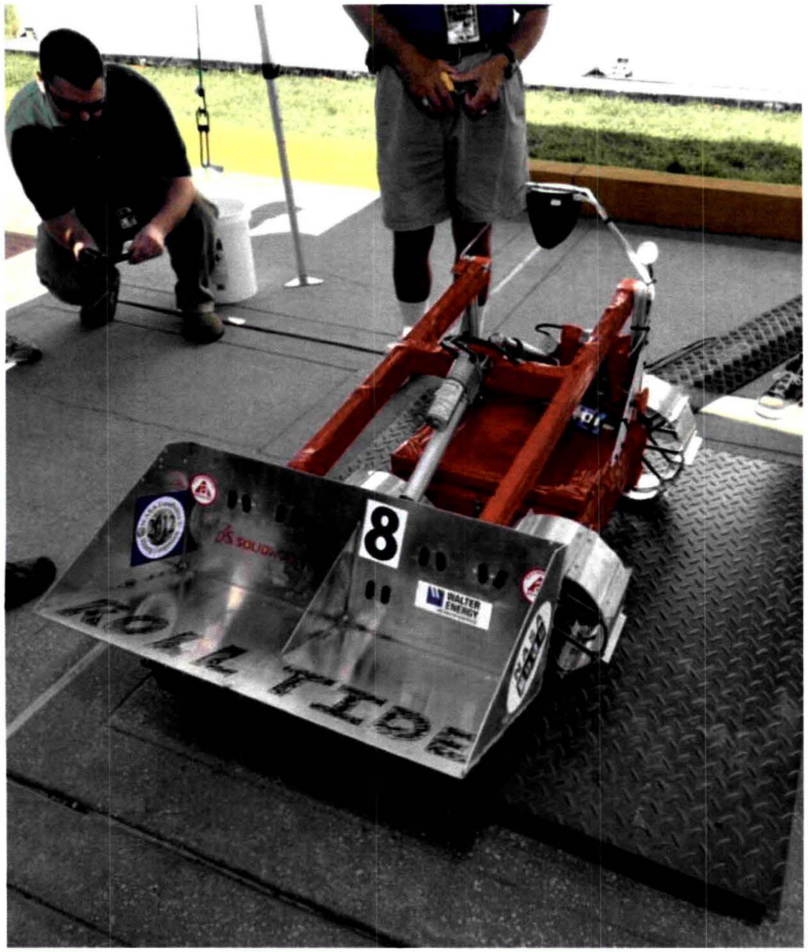
NASA Lunabotics Mining Competition Robot Systems 2010 - 2011



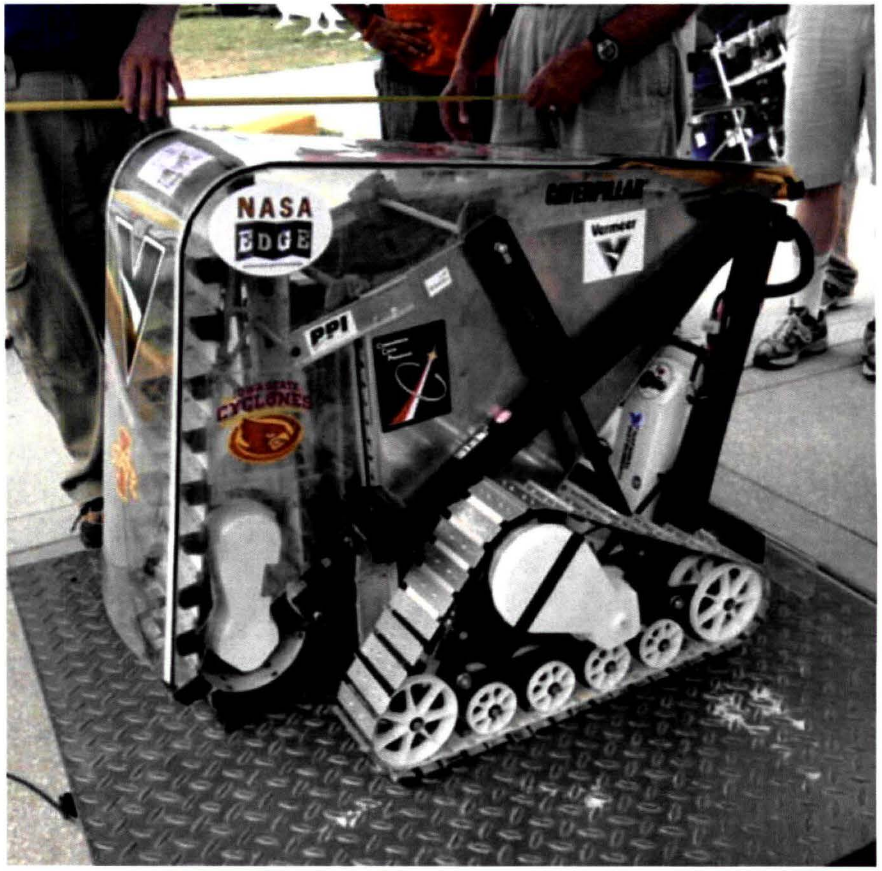
2010 Lunabotics Mining Competition
Winner: Montana State University
"The Mule" Lunabot,
from Bozeman, Montana

2011 Lunabotics On Site Mining Category
Winner: Laurentian University
"Production" Lunabot,
from Sudbury, Canada

2012 Lunabotics Mining Winners



U Alabama – Grand Prize



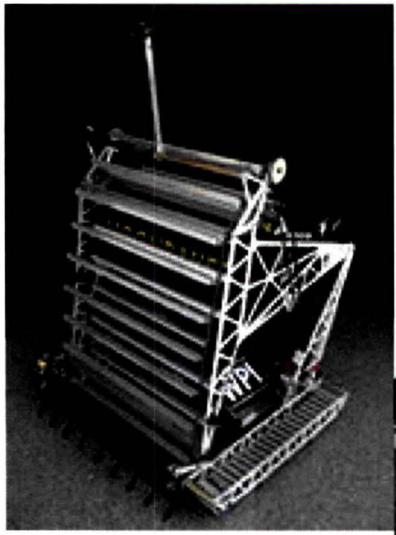
Iowa State U – On Site Mining Category

2013 Lunabotics Mining Winners

Iowa State U – 1st Place On Site Mining Category & Grand Prize

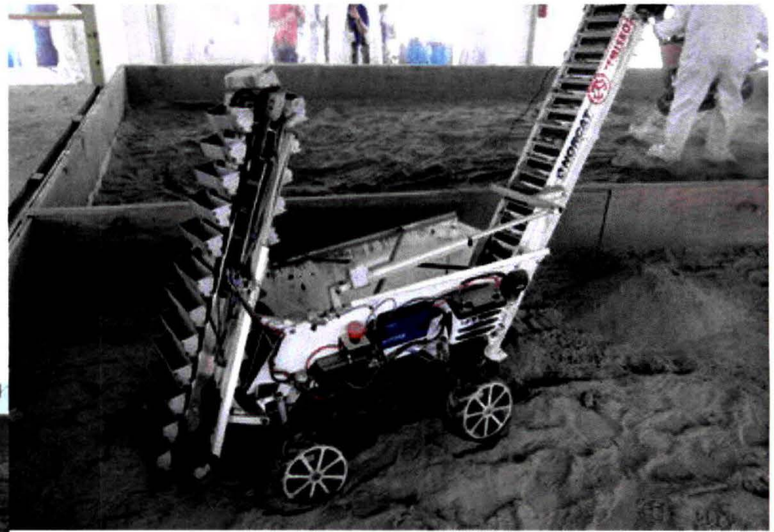
North Dakota – 2nd Place On Site Mining

What is the Most Popular Winning Design the Best Lunabot Regolith Mining Design for the Moon??

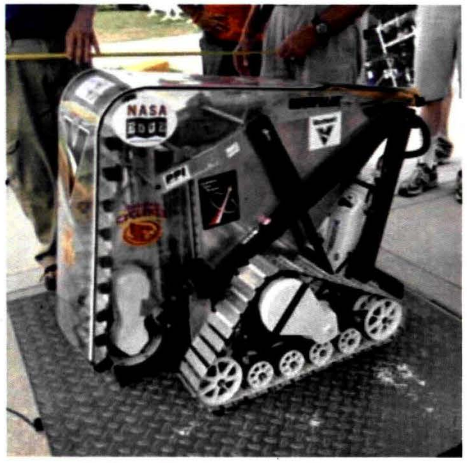


2009: Paul's Robotics WPI

2010: Montana State U

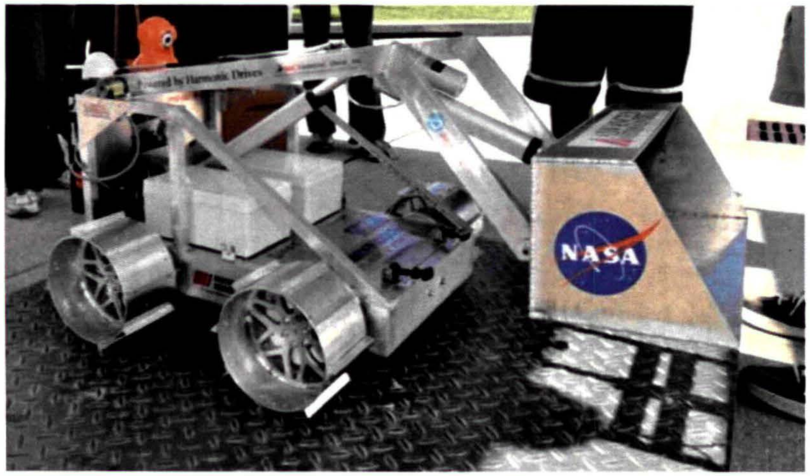


2011: Laurentian University

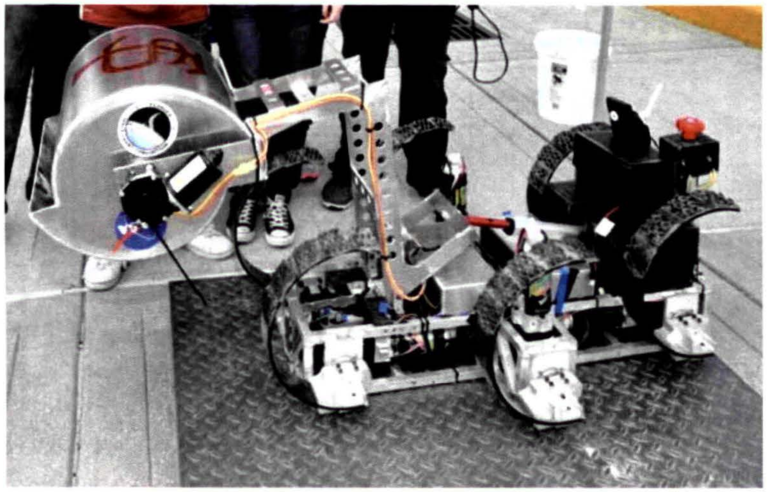


2012: Iowa State U

Or are these designs better?



2012: Embry Riddle Daytona



2012: FAMU/ Florida State U

2011: U North Dakota

2012: Montana State U

Top Robotic Technical Challenges*

- Object Recognition and Pose Estimation
- Fusing vision, tactile and force control for manipulation
- Achieving human-like performance for piloting vehicles
- Access to extreme terrain in zero, micro and reduced gravity
- Grappling and anchoring to asteroids and non cooperating objects
- Exceeding human-like dexterous manipulation
- Full immersion, telepresence with haptic and multi modal sensor feedback
- Understanding and expressing intent between humans and robots
- Verification of Autonomous Systems
- Supervised autonomy of force/contact tasks across time delay
- Rendezvous, proximity operations and docking in extreme conditions
- Mobile manipulation that is safe for working with and near humans

*NASA Technology Area 4 Roadmap: Robotics, Tele-Robotics and Autonomous Systems (NASA, Ambrose, Wilcox et al, 2010)

Top Space Mining Technical Challenges

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- Low reaction force excavation in reduced and micro-gravity
- Operating in regolith dust
- Fully autonomous operations
- Encountering sub surface rock obstacles
- Long life and reliability
- Unknown water ice / regolith composition and deep digging
- Operating in the dark cold traps of perennially shadowed craters
- Extreme access and mobility
- Extended night time operation and power storage
- Thermal management
- Robust communications

Conclusions

- There are vast amounts of resources in the solar system that will be useful to humans in space and possibly on Earth
- None of these resources can be exploited without the first necessary step of extra-terrestrial mining
- The necessary technologies for tele-robotic and autonomous mining have not matured sufficiently yet
- The current state of technology was assessed for terrestrial and extra-terrestrial mining and a taxonomy of robotic space mining mechanisms was presented which was based on current existing prototypes
- Terrestrial and extra-terrestrial mining methods and technologies are on the cusp of massive changes towards automation and autonomy for economic and safety reasons
- It is highly likely that these industries will benefit from mutual co-operation and technology transfer